Innovator or Imitator: A Critical Review of Sir John Soane's Mastery of Daylighting

"The history of architecture is the history of man's struggle for light - the history of the window." Mies van der Rohe

MSc Light & Lighting
Victoria Jerram

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1 Summary

Sir John Soane is widely regarded as a daylighting innovator and a master of top-lighting, yet many of Soane's contemporaries also used top-lighting. Historical research shows that top-lighting was a widely employed technique in the eighteenth and nineteenth centuries, both for aesthetic and functional reasons. While much has been written about the picturesque nature of Soane's top-lit spaces, there has been little analysis of daylight performance. His reputation appears to be based on dogma, rather than objective judgement. This report redresses the balance through examination of two of Soane's buildings, Dulwich Picture Gallery and the Court of Chancery. Computer models were constructed and used to measure daylight factors and predict sunlight penetration. Daylight performance over time was calculated from the measured daylight factors and the CIE IDMP diffuse illuminance probability data set for Garston, UK, based on a useful daylight illuminance range between 100 and 2,000 lux. These two case studies show that, as built, both interiors were underlit by today's standards, and justify contemporary complaints of inadequate light.

2 Introduction

This report reviews the basis on which Sir John Soane's reputation as a daylighting innovator and master of light is founded. The aim of the report is to understand if this reputation is justified, through historical investigation of contemporary daylighting and appraisal of Soane's daylit interiors. In order to achieve this aim, two case studies were chosen – Dulwich Picture Gallery and one of Soane's Westminster Law Courts, the Court of Chancery. The objectives of the case study appraisals were to:

- understand Soane's working practices with regard to daylight design
- determine daylighting performance using daylight factors, useful daylight illuminance and prediction of sunlight penetration

After a brief biography of Soane, the importance of daylighting is explained. There are many forms of daylighting: top-lighting is the form for which Soane is best known, and therefore constitutes the scope of this report. An introduction to top-lighting is followed by an account of Soane's use of top-lighting. An exploration of the use of top-lighting by Soane's contemporaries is then needed before moving onto the case studies. For each case study, the historical context of the building type (picture gallery and law court) is discussed, before the construction history is described, with particular focus on daylight design decisions.

Next, the methodology used to assess daylight performance is explained, covering the measurement methods chosen (daylight factor, annualised illuminance probability and sunlight penetration), the tool selected (computer modelling using AGI32 software package), and the tests performed. Scale drawings of each case study building are also presented here. The results are then presented in graphical format, accompanied by a short explanation. Following the results is an overview of Georgian window design and a discussion of the findings, analysing each site in the context of location, orientation, form, function, fenestration and glazing.

Finally, the findings are summarised and a conclusion is reached on Soane's daylighting reputation, based on objective judgement of these findings. This report will be of interest to architects, architectural historians and lighting designers.

This report is based on archival resources of the Sir John Soane Museum, other published sources and computer daylight models.

3 Background

3.1 Life and Work of Sir John Soane

John Soane was born in 1753, the son of a bricklayer in Goring-on-Thames. After his father's death in 1767, the family moved to Chertsey. Through local connections, Soane obtained employment with the architect George Dance the Younger and moved to London in 1768. Soane enrolled at the Royal Academy of Arts in 1771, and, as was the practice for architecture students, continued to work, for George Dance and then Henry Holland from 1772. During his time at the Royal Academy, Soane won various medals, culminating in the ultimate prize of a three-year travel scholarship in 1777. He left for Italy in 1778 where, over the next few years, his first-hand experience of classical architecture and connections made with future clients, patrons and friends were to be hugely influential for the rest of his career.

One of these potential clients, the Bishop of Derry, persuaded Soane to return home a year early in 1780, with the promise of work. The commission failed to materialise, and a disappointed Soane started his own practice first in East Anglia, and later in London. His buildings in these early years were principally country houses, such as Chillington Hall (1785-1789). In 1784 Soane married Eliza Smith, the niece of George Wyatt, a wealthy builder. Helped by Soane's connections made in Italy, he received his first major public position as surveyor to the Bank of England in 1788. In 1790 Soane's father-in-law, George Wyatt, died leaving Soane financially independent.

Soane continued to build his practice however, and further public appointments followed. In 1792 and now with two sons, Soane bought 12 Lincoln's Inn Fields as the family home. Prior to Soane's election as Professor of Architecture at the Royal Academy in 1806, his key works were the rebuilding of 12 Lincoln's Inn Fields, the Bank Stock Office, Bank Rotunda, Tyringham Hall, and his country retreat, Pitzhanger Manor in Ealing. Through the buildings of this period, Soane's personal style can be seen developing with such themes as the pedentive dome, starfish ceiling, arches and top-lighting. Parry considered Soane's predilection for top-lighting to "be his most fundamental characteristic" [1], and it is that daylighting technique that this report focuses on.

The next period of Soane's life has been described as his picturesque period [2], in which he concentrated on the "poetry of architecture" using dramatic daylighting effects. During this time Soane was engaged in preparing and delivering a series of lectures on architecture at the Royal Academy: public works continued with the Royal Hospital at Chelsea and further Bank halls. Other notable works of this period are the Dulwich Picture Gallery and the redevelopment of 13 Lincoln's Inn Fields. In his personal life, Soane realised, to his great disappointment, that his sons would not continue his architectural dynasty and sold Pitzhanger Manor in 1810. Soane's younger son anonymously published two articles viciously criticising his father's work, followed within a few months by Eliza Soane's death in 1815.

From 1820 to 1833, the final period of Soane's career was spent on official works where his designs attracted criticism as Gothic taste prevailed. His lack of patience with civil servants did not help the survival of his work from this time [3] most of which was subsequently destroyed. The Westminster Law Courts and Board of Trade Privy Council Chamber no longer exist, while some of the Downing Street interiors live on. Soane continued to develop the Lincoln's Inn Fields site, acquiring No. 14 in 1823, and in 1833 he endowed 13 Lincoln's Inn Fields to the nation as a museum. Soane's achievements were finally recognised by a knighthood in 1832 and he died in 1837, four years after retiring.

3.2 *Importance of Daylighting*

"The history of architecture is synonymous with the history of the window and of daylighting" [4]. Why is daylighting so important?

In the eighteenth century the electric light was yet to be invented. Sir Humphrey Davy invented the electric arc lamp in 1801 but it was not until the late nineteenth century that electric lighting became a viable light source with the introduction of the incandescent lamp and the electric generator. Artificial light was instead provided by candles, oil and gas lamps. As these sources were relatively expensive and provided only limited illumination, daylight was the de facto light source for living and working activities.

Developments in electric lighting continued throughout the twentieth century as the relative cost fell. This progress, combined with new construction materials and techniques, continued at such a pace that, by the mid twentieth century, daylight was seen as a luxury addition to primary electric lighting. The end of the twentieth century brought renewed interest in the use of daylight in buildings. Growing concerns over climate change and the reliance of our society on non-renewable energy sources, have led to a focus on reduction of carbon emissions (now generally accepted to be the cause of climate change) and energy consumption: electric lighting accounted for up to 6% of the United Kingdom's total energy consumption in 2002. Increased use of daylight reduces the use of electrical energy and helps address these sustainability issues. Human factors have also affected today's view on daylighting. Daylight is important for modelling and orientation; a view outside, the variety of daylight and the effect of sunlight have psychological impacts; physiologically we now know that daylight triggers Vitamin D production, and governs our circadian system.

3.3 *Top-lighting*

Top-lighting is the entry of natural light into a space through an opening in the ceiling of a building. The origins of top-lighting are in the unglazed apertures of the Pantheon, Rome, and the bazaars of ancient Persia [5]. Top-lighting spaces in the form of tribunes first appeared in English country houses in the early eighteenth century, the first documented example being a design by Colen Campbell in 1715 [6]. The tribune was a square or circular full-height room, top-lit by a dome and surrounded by a first floor gallery.

Top-lighting is an efficient form of daylighting, as it can provide uniform daylight distribution with minimum glazing area. The main advantage over side-lighting is the lack of restrictions on placement, and hence ability to deliver daylight into the centre of deep plan buildings. In contrast, side-lit buildings are constrained in their plan depth in order to achieve adequate light penetration (a common rule of thumb is that a room may be said to be adequately daylit when the plan depth is twice the head height of the window [7]).

Further advantages are the provision of either uniform distribution or a required pattern of light, and functional solutions such as privacy, security and freeing of walls for display. Daylight obstruction is also less likely. Top-lighting does not provide an exterior view, however sunlight patterns on the walls or floor can be an agreeable alternative. Both direct and reflected daylight give sufficient information about external conditions to orientate occupants of a top-lit space. [8]

A limitation of top-lighting is that it can only be used for the top floor of a building, unless lower floors are connected via an atrium or lightwell. Glare and thermal gain are also potential issues for top-lighting (as for all types of daylighting), however in eighteenth century England, with smoggy city skies and less efficient heating and insulation of buildings, these issues may not have been viewed with the same importance as today.

3.4 Soane's Use of Top-lighting

Soane's trademark use of top-lighting seems to have been despite the contradictory stance in his lectures that top-lighting was more appropriate for use in warmer climates [9]. Soane was drawn to the effects that top-lighting could produce, and the opportunities for manipulating light through different types of aperture and glazing. He subscribed to the principle, proposed by both Chambers and Le Camus, that quality of light affects the character of a building [10]. Soane translated Le Camus's theory as "A well lighted and well aired building, when all the rest is well treated becomes agreeable and cheerful. Less open, less sheltered, it offers a serious character: the light still more intercepted, it is mysterious or gloomy". This was the source of Soane's lumiere mysterieux [11]. His long career and busy practice meant that Soane had many opportunities to experiment with the effects of light. Gandy's perspective paintings, commissioned by Soane in order to attract clients, could have helped Soane visualise the effect of light in his designs [12], however Craddock has disproved this hypothesis [13] [1].

Soane used top-lighting in many of his country and town houses; lighting halls, staircases and tribunes with lanterns or rooflights, from Letton Hall (1783) at the beginning of his career to Pell Wall (1822-1828), his last country house. The picture gallery that Soane designed at Fonthill House is of particular significance: thought to be the first top-lit private picture gallery [14], it was to be a forerunner of Dulwich Picture Gallery (1811-1813). Soane used top-lighting extensively at his own home at Lincoln's Inn Fields; for example the Breakfast Room of No.12, the Dome, Picture Room, Monk's Parlour and Upper Drawing Office. Top-lighting was a necessity for many of his public buildings, governed by site limitations or functional requirements (privacy, security), as was the case for the Bank of England (1788-1833), Westminster Law Courts (1821-1824) and the Board of Trade Privy Council Chamber (1824). Top-lighting also allowed Soane to create atmosphere, evoking the different moods required by the Pitt Memorial at the National Debt Redemption Office (1817), the Royal Gallery (1822) - designed as part of the processional route at the Houses of Parliament - and the Dining Room at 11 Downing Street (1824-1825).

Figure 1 View over rear of Soane Museum

[1] Craddock modelled sunlight penetration of the Bank of England £5 Note Office, using a scale model in a heliodon, and compared the results with Gandy's renderings of the same date and representative time.

Soane's top-lighting strategies can be distilled into the following typologies: lanterns, roof lights and perimeter top-lighting. Many of these can be seen at the Sir John Soane Museum, used by Soane as a working laboratory, a microcosm of ideas. There were many variations on each theme, and Soane also used them in conjunction with each other and with side-lighting.

3.5 Use of Top-lighting by Contemporaries

The most influential of Soane's contemporaries was George Dance the Younger who, despite being Soane's first employer, was only twelve years older. Soane and Dance continued a close personal and professional relationship until Dance's death in 1825, despite the occasional rift caused by Soane's prickly nature [15]. Summerson has commented on the debt Soane owed to Dance for the development of his style, particularly in the design for the Bank of England [16].

Examination of Dance's work shows that he was also an enthusiastic proponent of top-lighting. Dance used this technique in various types of buildings from staircase halls in country houses (Ashburnham Park, Sussex, and Laxton Hall, Northamptonshire are two examples), to the Guildhall Council Chamber (1777-1778), the Shakespeare Gallery (1788-1789) and the Royal College of Surgeons, Lincoln's Inn Fields (1804-1810). Of particular interest is the design of the Guildhall Council Chamber, which was a rectangular space divided into a central area with flanking bays to the east and west. A pedentive dome, lit by a lantern covering the oculus, topped the square central space. The flanking bays rose to a higher level than the dome, with the dais in the west bay lit by hidden windows in the north and south walls. Many features of this design are familiar to us as, what were to become, Soane's leitmotifs [17].

Figure 2 Guildhall Council Chamber, George Dance the Younger

Figure 3 Royal College of Surgeons, George Dance the Younger with James Lewis

Another key figure of the time was Henry Holland. His inner vestibule or tribune at Bentham Park (1775) was designed while Soane was employed by Holland. Stroud credits this as "the prototype of a theme later adopted by Soane, and which became a feature of considerable importance in his works." [18]. Holland did not develop the use of top-lighting any further in his work, confining this solution to entrance halls, staircase halls and tribunes.

Robert Taylor, Soane's predecessor at the Bank of England, introduced top-lighting into his banking halls built between 1765 and 1787. The Rotonda (1765-1770) is well known, modelled as it is on the Pantheon in Rome. A lesser-known interior, built during the same phase of works at the Bank, is the Transfer Office. Here, Taylor designed a shallowly vaulted central space, described in the words of Stillman as lit "by three small circular domed lanterns, while the peripheral ambulatory space consisted of a series of individual bays, each topped by a lantern like those in the centre, thus creating a very interesting lighting effect." [19]. The Reduced Annuities Office (1780-1787) has already been suggested by Summerson as setting a precedent for the subsequent use of top-lighting in the Bank Stock Office by Soane [20].

Figure 4 Taylor's Reduced Annuities Office

Figure 5 Taylor's Transfer Office, Bank of England

Soane's study tour followed a well-trodden path around the buildings and sites of Italy [21]. Many of his fellow architects must have drawn inspiration from the same monuments. Other examples of the use of top-lighting in public buildings are Wyatt's Pantheon, Oxford Street, London (1769-1772); Cooley's Royal Exchange, Dublin (1769-1779); Robert Adam's Register House, Edinburgh (1772-1792); and Gandon's Four Courts, Dublin (1786-1796).

Figure 6 Royal Exchange Dublin (1769-1779), Thomas Cooley

Figure 7 Four Courts Dublin (1786-1796), James Gandon

This brief architectural survey shows that top-lighting was not the sole preserve of Soane. Contemporary architects also used top-lighting in a wide variety of public buildings from ballrooms to shire halls.

3.6 Previous Research

While many authors have commented on Soane's mastery of light, few have attempted to explain his work from a daylighting design perspective. Craddock's thesis "Sir John Soane and the Luminous Environment" [22] hypothesizes how Soane combined his thematic daylighting techniques with contemporary theories to produce his luminous spaces. Craddock postulates that Soane may have used architectural models to analyse the effects of daylight. This seems unlikely as models of this period were generally used for client presentations: constructed from expensive hardwoods, the quality of a model correlated to its function [23]. Fontoynont commissioned a daylighting study of two rooms at the Soane Museum (the Breakfast Room and the Picture Room) [24]. This study was based on physical measures of horizontal daylight factors and gives us a static view of daylight distribution within these two spaces. Parry's account [25] of Soane's work describes how Soane used daylighting to great effect, using the Bank of England, the Dulwich Picture Gallery and the Soane Museum as examples. Parry's work remains an historical sketch only, and both Phillips and Parry comment on the need for technical detail.

4 Research Question

Despite the disappearance of many of his buildings, Soane has been rediscovered in the last century as a "master of space and light" [26]. Soane's entry in the Illustrated Encyclopedia of Architects and Architecture reads, "Soane displays an originality and control that places him among a small group of architectural innovators. In his work he concentrates on the detailing of internal spaces and lighting." [27]

Has Soane fallen back into favour as thoughtlessly as he fell out of it after his death? Soane's mastery of light does not appear to have been critically tested with regard to the performance of his daylit interiors. Summerson has argued that Soane's work owes much to his mentor George Dance. Was Soane really an innovator in the use of daylighting, specifically top-lighting, techniques? This report re-appraises Soane's daylighting reputation against the backdrop of contemporary eighteenth century and early nineteenth century top-lighting.

5 Case Studies

This report uses two case studies to analyse Soane's working practices, in order to understand his thought process with regard to daylighting design. The criteria on which the case study selection was based are as follows:

- predominantly top-lit
- sufficient drawings exist in order to create computer daylighting model
- public buildings from different periods of Soane's life

5.1 Dulwich Picture Gallery

The origin of the picture gallery lies in the long gallery of the English country house [28]. The Uffizi Tribuna in Florence inspired Grand Tourists and architects alike to display paintings in specially designed spaces [29]. These galleries were increasingly top-lit in order to increase hanging space. Soane had designed toplit picture galleries earlier in his career at Fonthill House (1787) and Bentley Priory, Stanmore (1788-1790) [30]. Other late eighteenth century galleries using top-lighting were the Great Room at Somerset House by Chambers and Dance's Shakespeare Gallery[2], Pall Mall (1788-1789) in England; and the Salon Carré in Paris, into which top-lighting was introduced as a trial for the Grande Galerie's conversion into a museum [32].

Figure 8 Shakespeare Gallery, George Dance the Younger

[2] Stroud cites the internal arrangement of the Shakespeare Gallery as an influence in the design of Dulwich Picture Gallery [31]

Figure 9 Christies Auction Room, Pall Mall

Figure 10 William Chambers The Great Room, Somerset House

The nineteenth century brought a large number of paintings into Britain, as a consequence of the French Revolution. This stimulated both interest in art and the demand for galleries open to the public. In the first decade of the century Tatham built three galleries at Castle Howard (1800-1801), Cleveland House, St. James (1800-1806) and Brocklesby Park (1807), and acted as executant architect for Thomas Hope's Gallery at Duchess Street (1799-1803) [33]; while Nash built a gallery at Attingham Park (1807).[34]

Sir John Leicester built a gallery at his London house on Hill Street in around 1806, whose design has been attributed to Thomas Cundy [35]. Its remarkable likeness to a Soane interior led Watkin to surmise Soane's involvement [36], although no supporting evidence has been found in Soane's extensive archives[3].

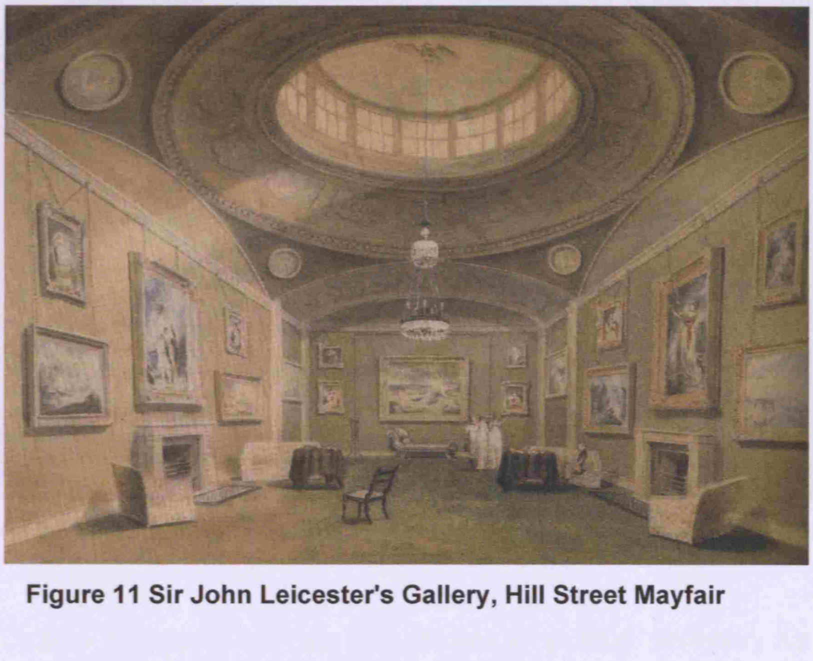


Figure 11 Sir John Leicester's Gallery, Hill Street Mayfair

[3] Soane's commissions in London have recently been fully catalogued, listing all recorded clients [37]

All these fore-runners of Dulwich were either conversions of, or additions to, existing spaces. Hence, Dulwich is considered to be the first purpose built picture gallery. [38]

Figure 12 Dulwich Picture Gallery (detail), drawn by Joseph Michael Gandy, 1823

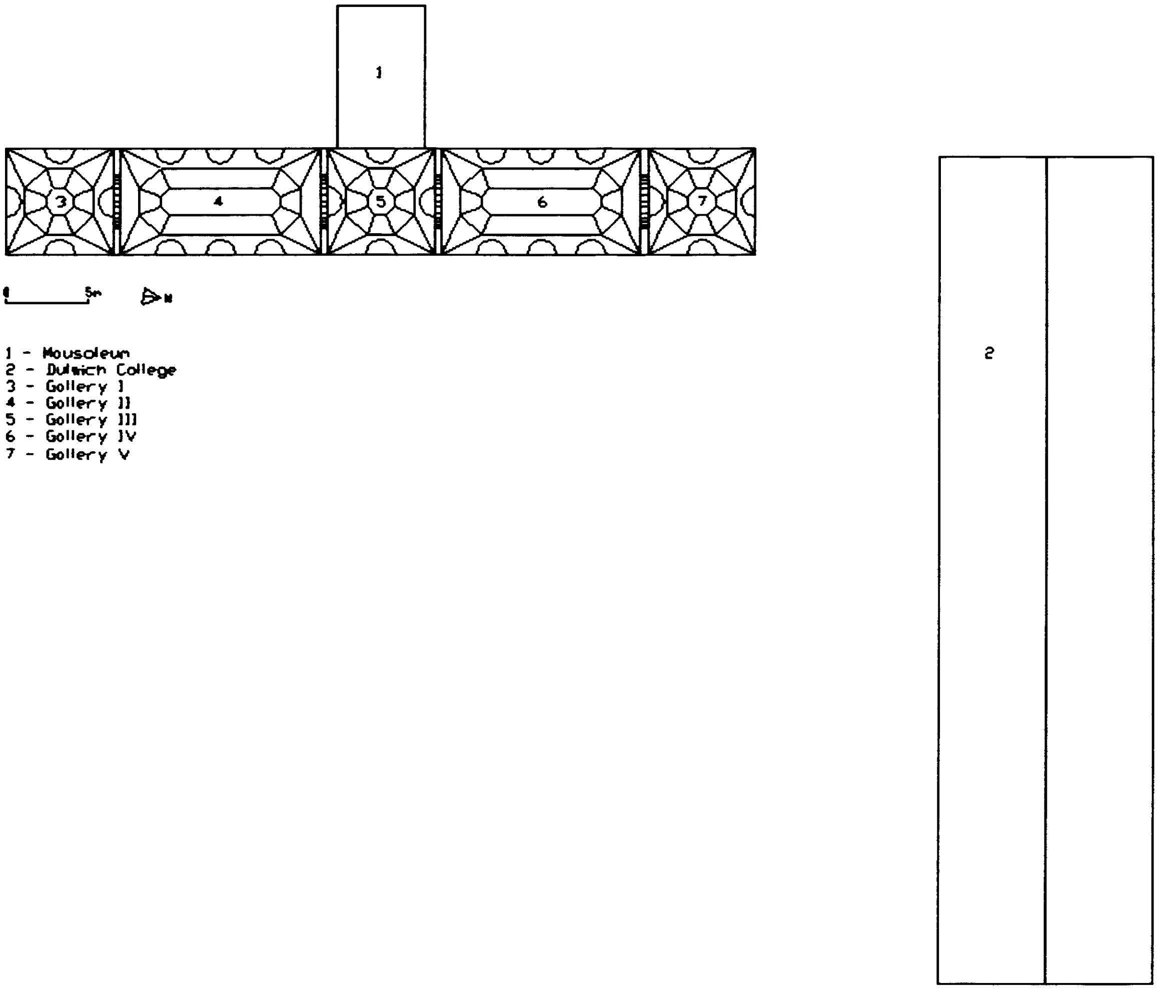


Figure 13 Dulwich Picture Gallery plan, based on SM 65/4/61

Soane began designing the gallery at Dulwich in 1811. The building was to accommodate not only a picture gallery, but also almshouses and a mausoleum. Very early designs, from April 1811, show Soane's intention to use top-lighting right from the outset. These plans also show the gallery set in a new quadrangle. Soane experimented with the orientation of the gallery, moving it briefly from the original east-west orientation perpendicular to the chapel to a position opposite the chapel facing north-south. The roof-lighting can be seen evolving through the design drawings from rectangular lanterns, to alternating rectangular and circular lanterns in May 1811, progressing to all circular skylights with sloped glazing later in the same month. The tight budget meant that sloped glazing was rejected due to its cost[4]. For the same reason Soane's dreams of a quadrangle were also rejected and the gallery, almshouses and mausoleum were combined into a single block. At this stage, the gallery was to be on the first floor with the almshouses beneath, but this was to change in the design of 10 July 1811. The gallery became two-storey, with the alternating circular and rectangular lanterns reflecting the alternating single-cube and double-cube room sizes below. This design was approved on 12 July, a few days later.

Despite approval of the plans, mid July saw Soane proposing clerestory lighting. By the end of the month this changed again to the octagonal rooflights of the design as eventually built. The foundations were laid on 19 October 1811. The start of building did not prevent Soane revisiting the clerestory windows throughout October, trying both 3-

[4] See section 8.1 for description of glass tax

light and elongated 5-light versions. In March 1812 Soane reverted back to octagonal rooflights; four months later, progress drawings show the roof-light frame in position. The gallery was completed in 1813 with the pictures hung in September 1814, and was open to selected visitors the following year. The general public were admitted from 1817. [39]

The gallery was criticised initially for its poor lighting by Hazlitt and Farrington. Farrington also commented on the wall colour, a dark burnt ochre (venetian red) recommended by Benjamin West (President of the Royal Academy, and royal painter to King George III). Soane too found the colour unsuitable for the paintings, and paid for the repainting of the gallery in a lighter colour, at his own expense in 1829. Earlier the same year, the ground glass of the lanterns was replaced for clear glass, perhaps in response to continued comments on the dimness of the lighting. [40]

Criticisms of inadequate light persisted through the Victoria era, and were eventually acted on with the introduction of sloped glazing in the lanterns between 1912 and 1915 [41]. A recent architectural survey suggests that these criticisms were actually due to the perception of insufficient light, as a result of glare and uneven illumination [42]. Electric lighting was installed at Dulwich Picture Gallery in 1974, but the Gallery remains predominantly daylit today.

5.2 Court of Chancery

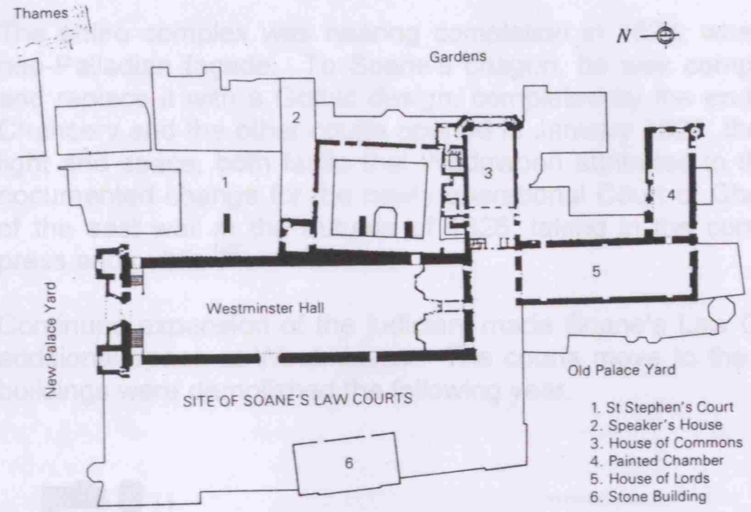
Soane's involvement with the Law Courts at Westminster started in 1818 with a fireproofing survey. The Law Courts had been at Westminster since the late thirteenth century; and the Court of Chancery, together with the Court of the King's Bench, was situated at the south end of Westminster Hall.

The Court of Chancery no longer exists in the British twenty-first century legal system; in the nineteenth century, the Court of Chancery was a court presided over by the Lord Chancellor on behalf of the King, evolved out of the exercise of royal prerogative over the courts of common law. Cases were determined on the basis of equity, or fairness, and included both commercial law and probate, as dramatically described by Dickens in his novel of 1852, Bleak House. The judicial system was expanding, as a result of the advancing industrial revolution and consequent economic development. This led to Soane's commission in 1820 to relocate the Court of Chancery and the Court of the King's Bench to a new site, to the west of the Hall. The project scope soon extended to the rebuilding of the whole judicial complex; seven courts in total with amenities.

Thomas Kent's Common Pleas Court, already sited to the west of the Hall, served as a model. Fitting between a pair of buttresses and joined to Westminster Hall by an opening, it was top-lit. The advantages of top-lighting for courtrooms are privacy and security, and this practice was followed at other courts of the time, including Cockerell's Westminster Sessions House, Thomas Rogers' Middlesex County Sessions House and John Harvey's Staffordshire County Hall.

Figure 14 Thomas Rogers Middlesex County Sessions House, 1778-1782

Figure 15 John Harvey Staffordshire County Hall, 1795-1799



The site was constrained, set between Westminster Hall and St. Margaret's Street to the east and west, and New Palace Yard and Old Palace Yard to the north and south.

Figure 16 Court of Chancery Site Plan

In response to the site limitations and functional requirement, Soane's design was principally top-lit interspersed with light courts. Building began in 1822, and in the Court of Chancery Soane produced an interior that Gandy's representations show as highly theatrical. The ground floor decoration was relatively simple, excepting a tripartite wooden canopy over the tribunal, with light oak panelling and white plaster walls. The oval gallery level was more ornate, supported by a very shallow pedentive dome pierced with oculi, topped by double rows of hanging arches and lit by side windows and a square lantern. The lantern was first fitted with a screen that Sawyer describes as "an extraordinary light-filtering device of circular diaphragms fronting rectangular openings", the design of which he considered to "have no precedent and constitutes one of Soanes most dramatic innovations" [43]. The screen was however removed in August 1823 [44], the most likely reason being that it obscured too much light.

Figure 17 Court of Chancery with lantern screen

The entire complex was nearing completion in 1824, when MPs complained about the neo-Palladian façade. To Soane's chagrin, he was compelled to demolish this façade and replace it with a Gothic design, completed by the end of 1825. When the Court of Chancery and the other courts opened in January 1826, there were complaints of lack of light and space, both faults that Wedgwood attributes to the site [45]. However the only documented change for the newly operational Court of Chancery was the reconstruction of the east wall in the autumn of 1826, taking in the corridor to create more room for press and public [46].

Continued expansion of the judiciary made Soane's Law Courts obsolete: there was no additional space at Westminster. The courts move to the Strand in 1882, and Soane's buildings were demolished the following year.

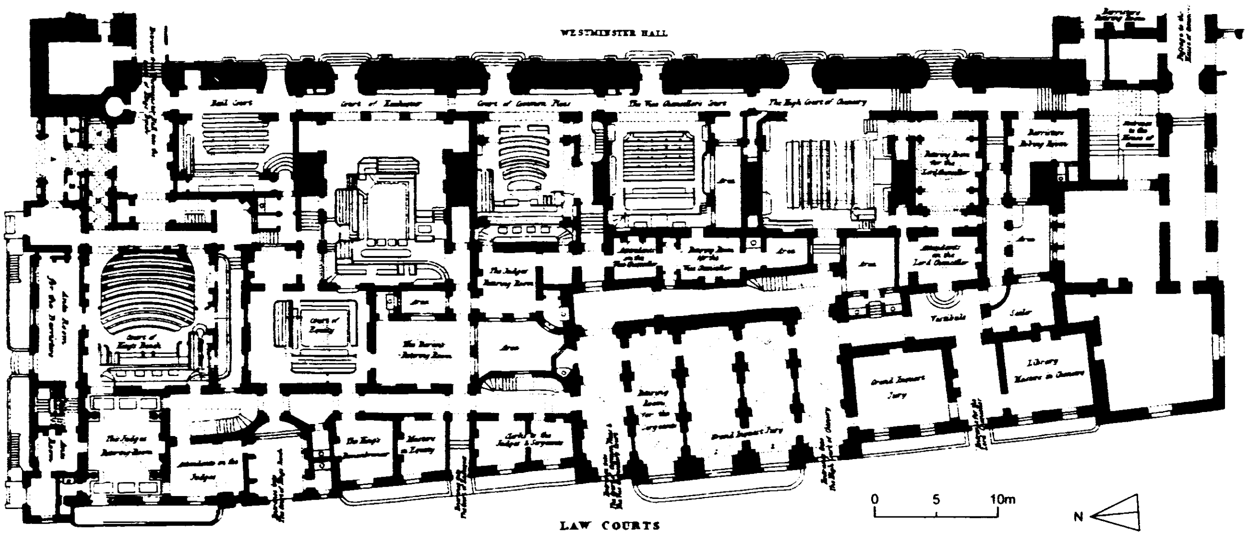


Figure 18 Soane's Westminster Law Courts Complex

6 Methodology

6.1 Tools and Techniques

The objective of the quantitative part of this study was to assess daylight performance of the selected case studies, Dulwich Picture Gallery and the Court of Chancery. The methods chosen to make these assessments were daylight factors, annualised illuminance probability and sunlight penetration.

The daylight factor is expressed as the internal illuminance at a particular point as percentage of the simultaneously available external illuminance from an unobstructed sky of known luminance distribution. It is the daylight prediction method on which current professional guidance is based [47]. Other methods such as daylight coefficients and more recently climate-based modelling exist, however these are not widely utilized. Daylight factors, typically measured under the CIE Overcast Sky distribution model, represent a worst-case scenario. The advantages of the daylight factor are that it provides data for daylight distribution diagrams, and can be obtained by measurement under the real sky, or using scale or computer models. A limitation is that location and orientation are not taken into account. For this reason annualised illuminance probability was calculated from the CIE (Commission Internationale de l'Eclairage or International Lighting Commission) International Daylight Measurement Programme diffuse illumination data set for Garston, UK [48], on the assumption that this data is not significantly different from that at the case study locations in the first half of the nineteenth century. The International Daylight Measurement Programme (IDMP) diffuse data is provided as a set of probabilities for the measured diffuse illuminance range in 1,000 lux intervals for each hour of a single day in each month. Annualised illuminance probability provides annual lux hours (used for measuring light exposure in galleries) and probability of useful daylight illuminance. As the illumination data set used contains only the diffuse daylight element, the results obtained do not take into account the direct daylight element. The highest average illuminance in the diffuse annual data set is 67,000 lux (in June), but on clear or partly clear days, levels of daylight illuminances will be much higher as both diffuse and direct daylight elements will be present.

Nabil and Mardaljevic define useful daylight illuminance, or UDI, as the occurrence of illuminances over the measurement plane, where all the illuminances are within the range 100-2,000 lux. Nabil and Mardaljevic base these limits on a survey of published occupants preferences and behaviour. Daylight illuminances of less than 100 lux are considered to be insufficient, i.e. too low for visual perception or performance of visual tasks, while levels greater than 2,000 lux are likely to cause thermal or visual discomfort. [49]

By studying sunlight penetration, it is possible to see the play of light within a space, and make judgements on the resultant effects.

Historical research shows that Soane made many revisions to his designs while building was in progress, and at Dulwich changes continued after completion. A series of sensitivity tests were defined in order to analyse the impact of such changes on daylight performance. Sensitivity tests for Dulwich examined the impacts of the glass type, paint colour, lantern glazing and window type. The Court of Chancery was tested for the impacts of the lantern screen. The contribution of inter-reflected light to the daylight performance in both case studies buildings was also explored, indicating the effectiveness of the surface geometry and reflectances.

Computer modelling was chosen as the most appropriate tool with which to implement the selected the analysis methods, for the following reasons:

- readily available and does not require the use of additional equipment such as an artificial sky, photocells and camera
- quicker to make changes to the models for sensitivity testing, than for scale models
- direct measurement under the real sky was not possible, as the Court of Chancery no longer exists

There are many computer software packages available with the ability to measure daylight performance. These packages vary in their sophistication and type of algorithms employed, ranging from Radiance to Relux. AGI32, by Lighting Analysts Inc., was selected for its combination of modelling capabilities and ease of use. AGI32 uses the radiosity technique, based on flux transfer principles. All objects defined in the model are subdivided into an imaginary mesh of elements, where the size of element depends on the size of the object. As light is emitted into the model, it will intersect elements in the direct line of sight. A certain amount of energy will be absorbed at this intersection, with the rest reflected or transmitted. Flux transfer continues until all light in the model is accounted for. Surfaces are treated as perfectly diffusing, making AGI32 fast and cost-effective, but less realistic than a ray-tracing package (such as Radiance) due to this surface simplification.

A further limitation of AGI32 is that it does not calculate daylight factors on the vertical plane. To overcome this, vertical illuminances were measured while recording the overcast sky illuminance level, and vertical daylight factors were calculated manually from these figures using the formula:

$$\text{Daylight Factor, DF (\%)} = \frac{I_i}{I_o} \times 100$$

where

I_i = internal vertical illuminance, lx

I_o = external overcast sky illuminance, lx

AGI32 was run using the following radiosity settings:

- Adaptive sub-division enabled for Exterior Daylighting
    - Maximum Subdivision Level = 5 (value recommended for daylighting)
    - Minimum Element Area = 0.1 (value recommended for daylighting)
    - Element Luminance Threshold = 1.1 (value recommended for daylighting)
- Adaptive sub-division enabled for Electric and Daylighting For All Other Surfaces
    - Maximum Subdivision Level = 5 (value recommended for daylighting)
    - Minimum Element Area = 0.0465
    - Element Luminance Threshold = 1.1 (value recommended for daylighting)

Three-dimensional models were built for both case study buildings, using dimension data obtained from copies of the eighteenth century architectural drawings held at the Sir John Soane Museum.

6.2 Error Sources

Sources of potential error were identified as:

- Dimensional accuracy of models, due to
    - measurement from sometimes indistinct copies
    - conversion from imperial into metric
- Simplification of obstructions
- Assumptions of glass material properties and transmissions

Sensitivity tests reduce the effect of potential errors, as all test cases are subject to the same errors and the focus of interest is the change in performance between test cases.

6.3 Dulwich Picture Gallery

A three dimensional model of Dulwich Picture Gallery was constructed in AGI32, using the following material properties:

Surface	Material	Colour	Reflectance
Walls	Paint	Dark mineral red	0.19
		Light mineral red	0.55
Floor	Oil cloth	Green	0.23
Coving	Paint	White	0.80
Lantern interior	Paint	White	0.80
Pictures	Paint	Various	0.09-0.41
Picture frames	Wood	Brown	0.44
Ground plane	Grass	Green	0.28
Dulwich College	Brick	Grey	0.30
Mausoleum	Portland stone	Cream	0.60
			Transmittance
Lantern glass	Glass	Clear	0.80
		Ground	0.70

AGI32 does not allow the modelling of diffuse glass with a transmission greater than 0.19, therefore the ground glass was modelled as clear glass.

The obstructions modelled were Dulwich College to the north of the gallery, and the mausoleum to the west.

Figure 19 Dulwich Picture Gallery West Section, based on SM 65/4/58

Figure 20 Dulwich Picture Gallery North Section, based on measured section courtesy of Stephen Cannon-Brookes

The geographical location is 51:26:47N latitude, 0:05:11W longitude, at an orientation of 007º north.

Dulwich Picture Gallery was modelled as accurately as possible from the available drawings. Records show that the gallery was salon hung[5] with the Bourgeois Collection, totalling 360 oil paintings, and contained furniture bequeathed by Mrs Desenfans. For simplicity, only 70 pictures were modelled and no furniture included. The clerestory window model assumes a plain interior, as no drawings exist to show how Soane envisaged this. The drawing on which the clerestory model is based, shows rectangular lanterns over galleries I and V. For ease of modelling, the same octagonal lanterns were used for all tests.

Figure 21 Dulwich Picture Gallery AGI32 Rendering

[5] Technique where paintings are hung close together without spaces, covering the whole wall surface

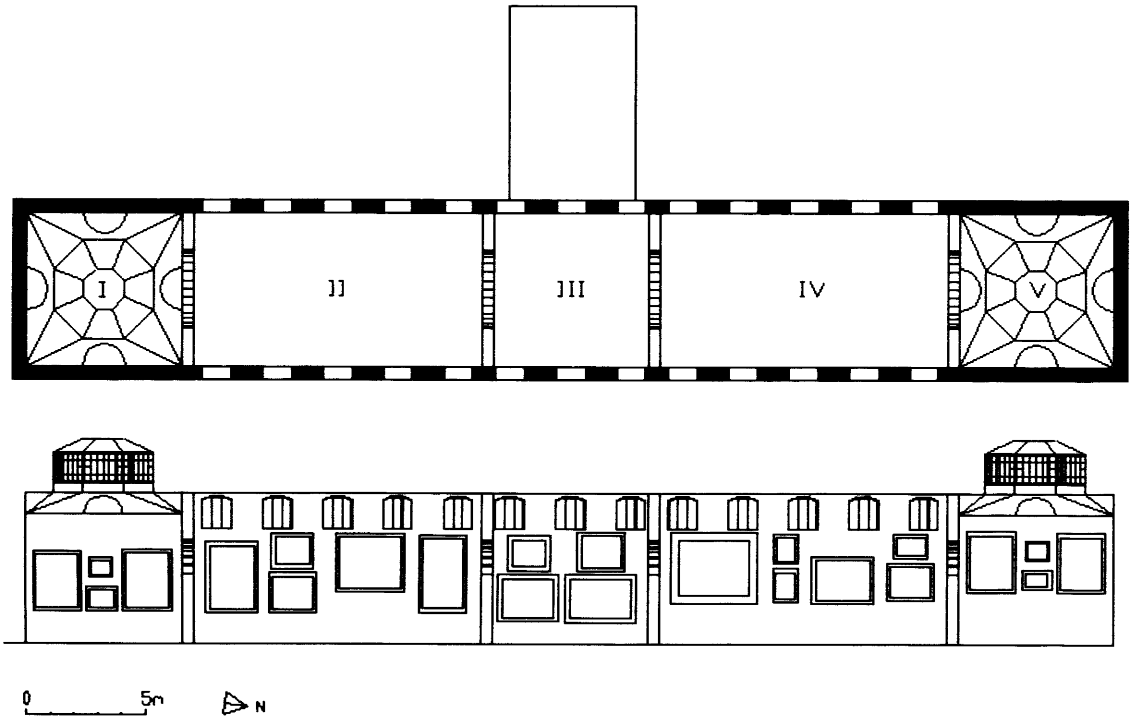


Figure 22 Clerestory window design, based on SM 15/1/05 (17 July 1811)

6.3.1 Daylight Factor Measurement

A 1m square vertical measurement grid was placed on each wall of the gallery facing into the room, at a distance of 0.1m in front of the wall and 0.34m above the floor plane. Each grid was centered horizontally across the wall, giving 6 measurement points across Galleries I, III and V, and 12 measurement points across Galleries II and IV. The vertical measurement plane was chosen, as the viewing of pictures is the primary task at the gallery.

The key variables impacting daylighting performance were identified as the wall colour, glass type and window type. The evolution of the gallery can be charted against these changing variables, defining the following sensitivity tests:

Test	**Revision Date**	**Variables**		
		Wall colour	**Glass type**	**Window type**
1	July/October 1811	Dark mineral red	Clear	Clerestory
2	1815 ***as built***	Dark mineral red	Ground	Vertically glazed lantern
3	Early 1829	Dark mineral red	Clear	Vertically glazed lantern
4	Late 1829	Light mineral red	Clear	Vertically glazed lantern
5	1912-1915	Light mineral red	Clear	Sloping glazed lantern

6.3.2 Annualised Illuminance Probability

Daylight is useful in an interior when it lies within the range 100 – 2,000 lux. Below 100 lux it becomes difficult to read gallery programmes. Above 2,000 lux the detail of darker paintings becomes lost, and veiling reflections from the highly varnished surfaces of the oil paintings inhibit vision. An acceptability threshold of 90% [50] was set for the probability that daylight within the space will be within the useful range 100 to 2,000 lux.

The IDMP diffuse data is provided as a set of probabilities for the measured diffuse illuminance range in 1,000 lux intervals for each hour of a single day in each month.

						January							
Illuminance Range (lux)	**Average Illuminance (lux)**	**0:00**	**1:00**	**2:00**	**3:00**	**4:00**	**5:00**	**6:00**	**7:00**	**8:00**	**09:00**	**...**	**23:00**
0 - 1	**0**	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.817	0.096	0.000		1.000
1 - 1000	**500**								0.183	0.458	0.024		
1000 - 2000	**1500**									0.235	0.120		
2000 - 3000	**2500**									0.113	0.154		
3000 - 4000	**3500**									0.072	0.133		
4000 - 5000	**4500**									0.020	0.108		
5000 - 6000	**5500**									0.006	0.102		
6000 -72000	**6500**										0.093		
7000 - 8000	**7500**										0.099		
8000 - 9000	**8500**										0.069		
9000 - 10000	**9500**										0.045		
10000 - 11000	**10500**										0.018		
11000 - 12000	**11500**										0.024		
12000 - 13000	**12500**										0.003		
13000 - 14000	**13500**										0.003		
14000 - 15000	**14500**										0.003		
...	**...**												
22000 - 23000	**22500**												

The sum of probabilities for each hour is 1, as in any given hour the measured diffuse illuminance must be within the total measured range. The monthly probability of the interior illuminance in the gallery being within the useful range, was determined as follows:

1. Using the average daylight factor for the whole gallery, calculate the lower external illuminance value required to achieve 100 lux internally, where $I_{low} = 100/DF_{av}$
2. Similarly calculate the upper external illuminance value required to achieve 2,0000 lux internally, where $I_{high} = 2{,}000/DF_{av}$
3. For each month
    a. For each hour between 10:00 and 16:00 inclusive, sum the probabilities between the calculated illuminance ranges I_{low} to I_{high}
    b. Calculate the average daily probability by weighting the average of the hourly probabilities
4. Plot the average daily probabilities for each month, noting how many months of the year the probability of the useful range exceeds 90% (threshold value)

The annual lux hours or total illuminance over one year, were calculated using the same data. The maximum daylight factor was used in order to obtain a worst-case scenario from a conservation perspective.

The calculation process was as follows:

1. For each month
   a. For each hour between 10:00 and 16:00 inclusive, multiply each average illuminance value by its associated probability and sum the results
   b. Multiply the result by the maximum daylight factor for the whole gallery
   c. Sum the hourly lux hours and multiply by the number of days in the month to obtain the monthly lux hours
2. Sum the monthly lux hours to obtain the annual lux hours

These calculations were performed for each test case.

6.3.3 Sunlight Penetration

Sunlight penetration was assessed under the CIE Clear Sky model, against tests 1, 2, 3 and 5. Test 4 was omitted as the only change from test 3 is the wall reflectance which does not impact sunlight penetration. A single viewpoint (looking north from gallery I towards gallery V) was chosen to view the interior at three dates, over hourly intervals during opening hours. Opening hours were assumed to be between 10:00 and 16:00 hours. The dates chosen were the summer and winter solstices (21 June, 21 December respectively) and the spring equinox (21 March), these dates being representative of the range of solar conditions over a year.

A single image was obtained for each hour on every date, giving a total of 20 samples for each test, omitting 21 December 16:00 due to lack of sunlight. For each image in which sunlight penetration was observed, sunlit areas were highlighted in yellow. All sunlit area highlights were amalgamated into a single image for each test, showing the total sunlight penetration area representative over the year. The saturation of the yellow highlights does not indicate variance in sunlight intensity, which was not measured. Any variation in saturation of the yellow highlights is due to sunlit areas occurring for more than one date/time. Individual images for all date/time samples can be found on the attached CD in Appendix II.

Sunlight penetration results were processed as shown in the following images, using Dulwich Picture Gallery Test 1 as an example.

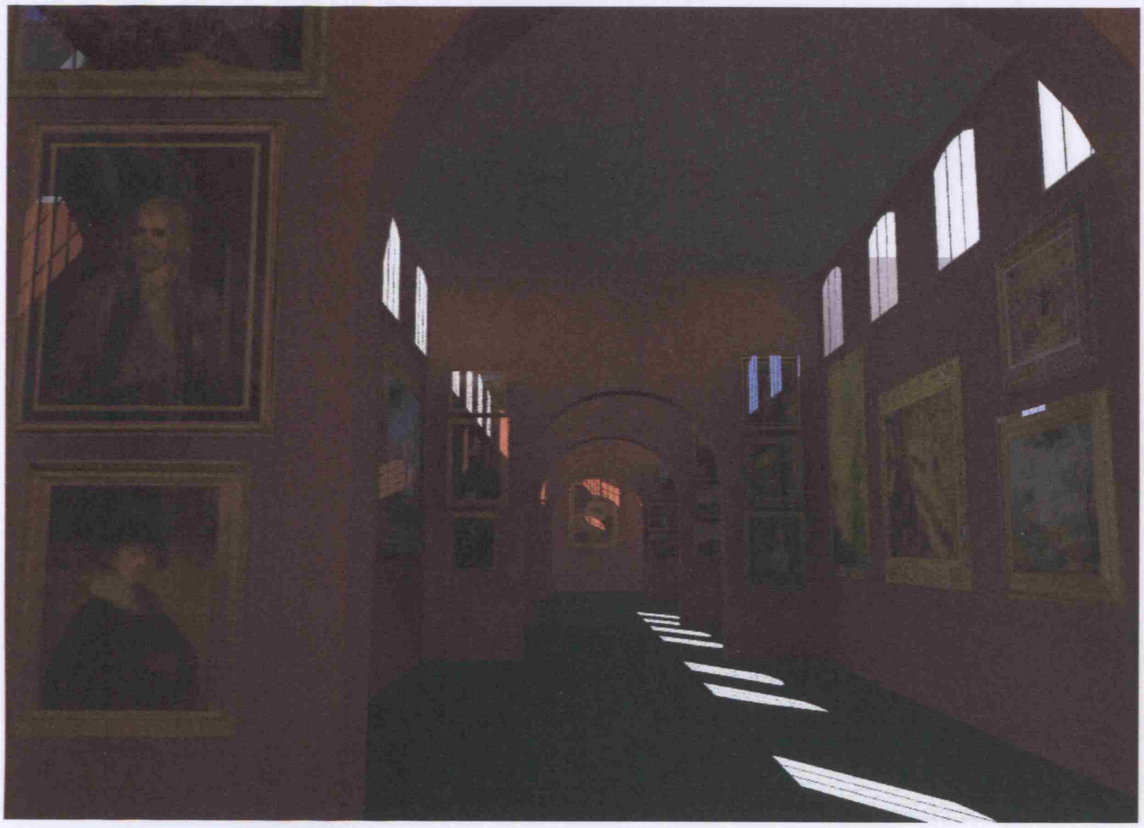


Figure 23 Dulwich Picture Gallery Test 1, 21 March 10:00 AGI32 generated image

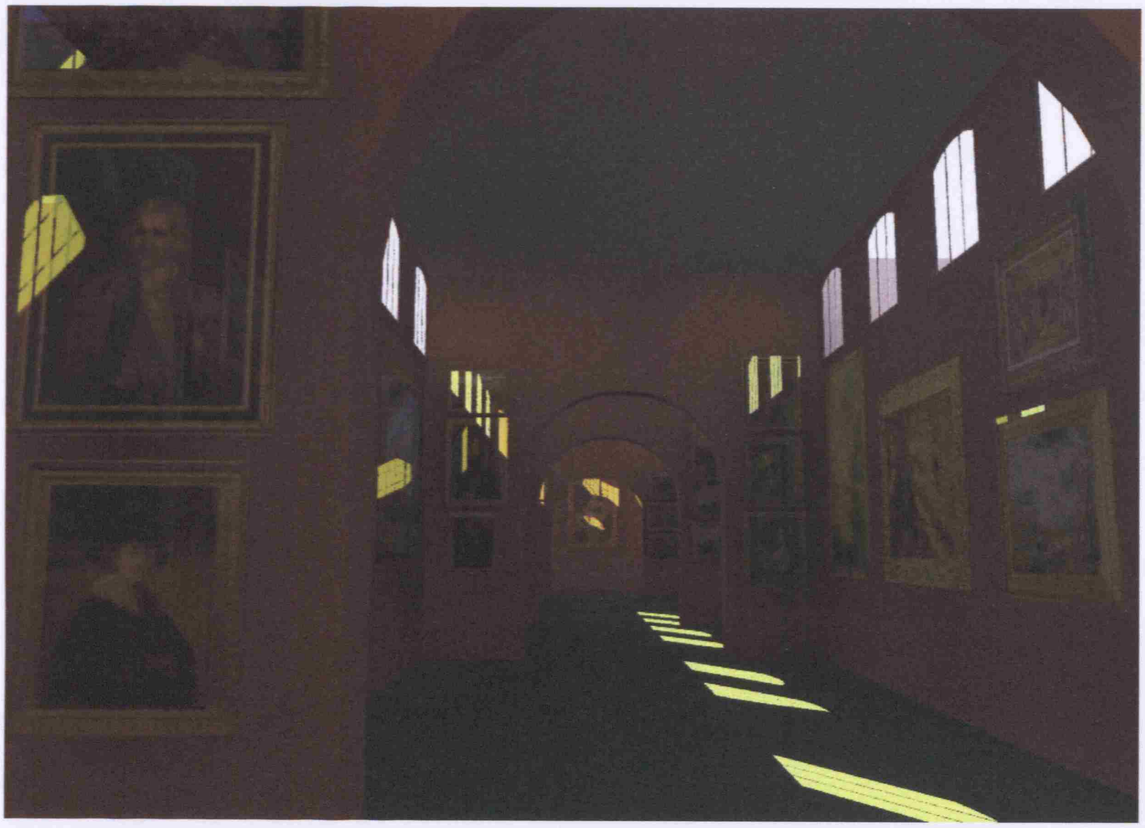


Figure 24 Dulwich Picture Gallery Test 1, 21 March 10:00 sunlit areas highlighted

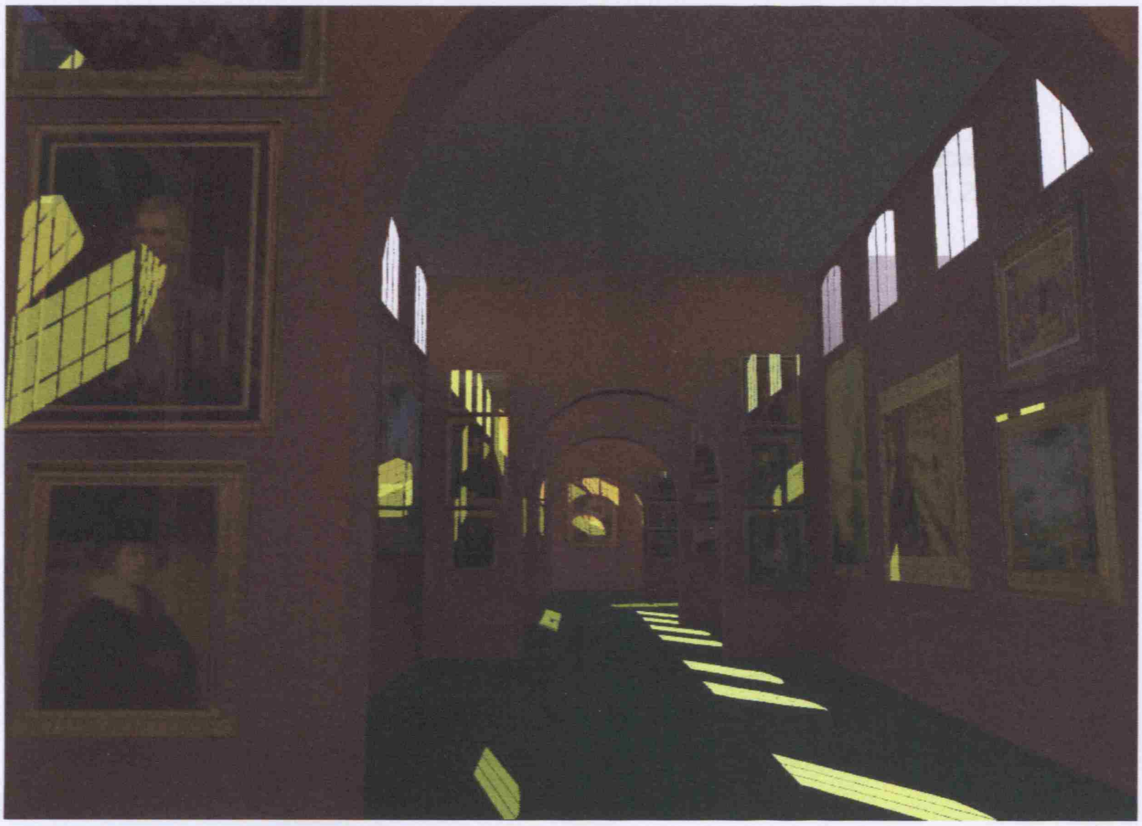


Figure 25 Dulwich Picture Gallery Test 1, 21 March 10:00 and 11:00

6.4 *Court of Chancery*

A three dimensional model of the Court of Chancery was constructed in AGI32, using the following material properties:

Surface	Material	Colour	Reflectance
Ground level panelling	Wood	Brown 	0.28
Ground level walls	Paint	White	0.80
Floor	Wood	Brown[6] 	0.28
Gallery level walls	Paint	White	0.80
Gallery level floor	Paint	White	0.80
Lantern interior	Paint	White	0.80
Ground plane	Stone	Grey	0.25
Exterior obstructions	Stone	Grey	0.25
			Transmittance
Lantern glass	Glass	Clear	0.80

The obstructions modelled were Westminster Hall to the east of the gallery, the Lord Chancellor's Retiring Room to the south, the Stone Building to the west and Vice Chancellor's Court to the north.

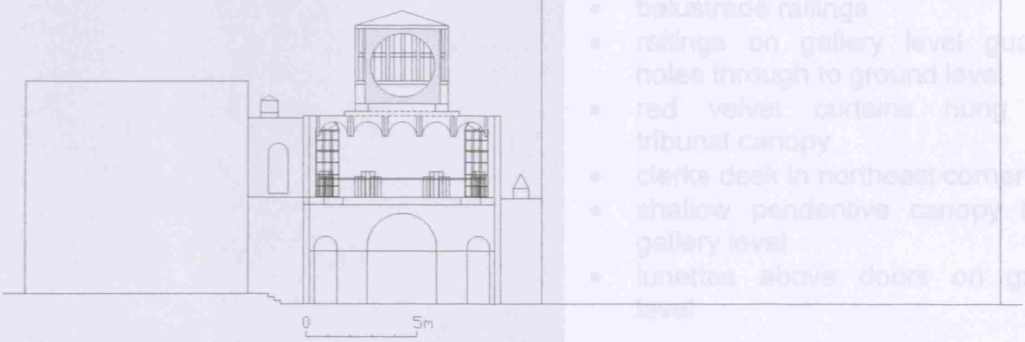


Figure 26 Court of Chancery North Section, based on SM 180362

[6] The floor may have been carpeted in red [51], however the reflectance is assumed to be similar

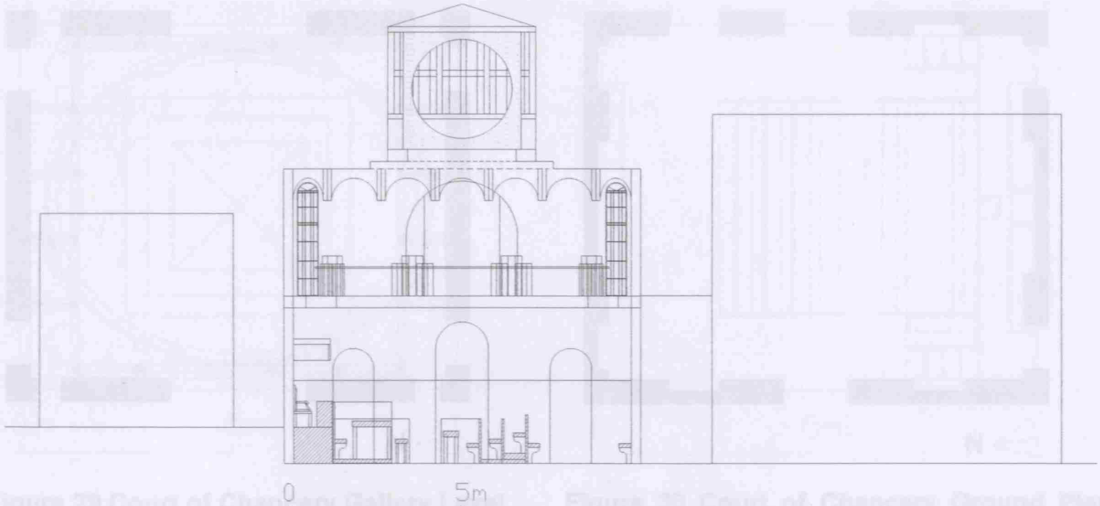


Figure 27 Court of Chancery West Section, based on SM 180361

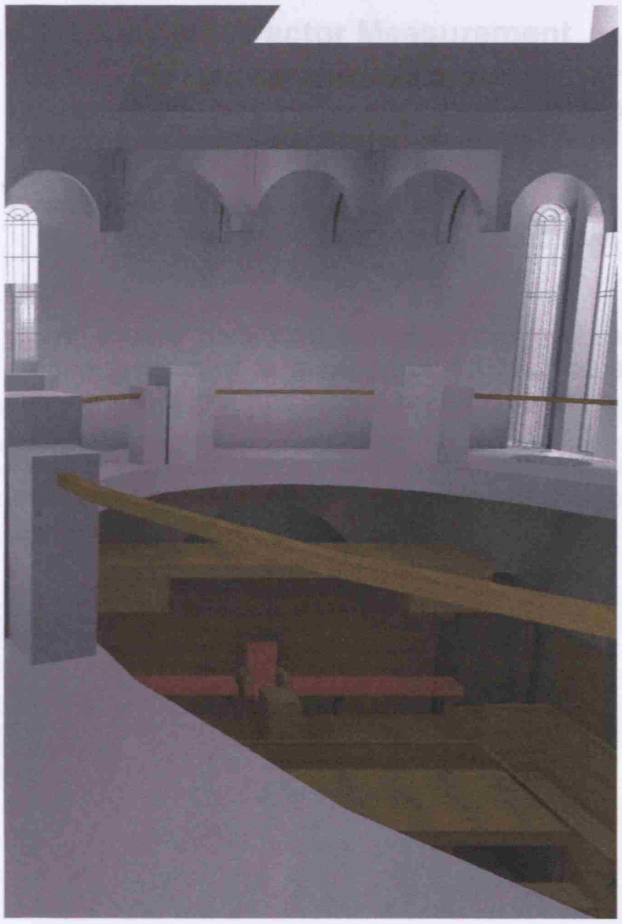


Figure 28 Court of Chancery AGI32 Rendering

The geographical location is 51:29:59N latitude, 0:07:32W longitude, at an orientation of 010º north.

The Court of Chancery was modelled as accurately as possible from the available drawings. The surrounding buildings in the Westminster Law Courts complex were simplified for ease of modelling, as were some of the Court of Chancery internal details. Internal details omitted were:

- finials of the hanging arches
- statues on the balustrade pedestals
- balustrade railings
- railings on gallery level guarding holes through to ground level
- red velvet curtains hung from tribunal canopy
- clerks desk in northeast corner
- shallow pendentive canopy below gallery level
- lunettes above doors on ground level

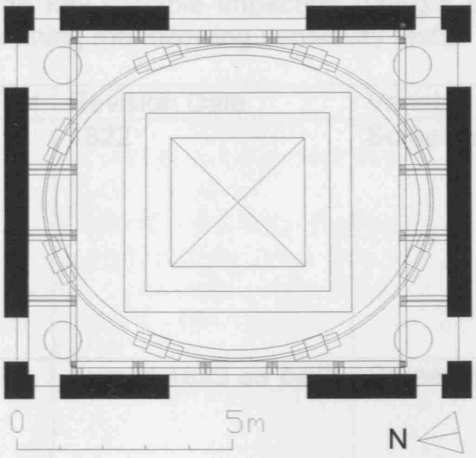


Figure 29 Court of Chancery Gallery Level Plan with Ceiling Plan, based on SM 3306/51

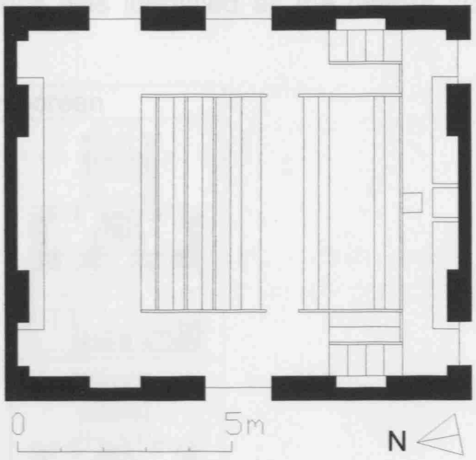


Figure 30 Court of Chancery Ground Plan, based on SM 3306/52

6.4.1 Daylight Factor Measurement

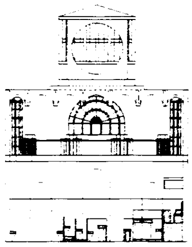
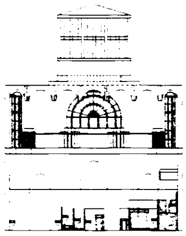
The Court of Chancery was not a criminal court, and therefore reading of court papers was assumed to be the primary task, and facial recognition a secondary task. Three horizontal working plane heights were selected:

Working plane height (m)	Location
1.10	Main ground level area
1.85	Dais

A 1m square horizontal daylight factor measurement grid was placed over the main ground level area at a height of 1.10m, and a 0.5m square horizontal daylight factor measurement grid was placed over the dais at a height of 1.85m.

Two vertical illuminance measurement grids, 0.5m square, were placed on vertical planes level with the Lord Chancellor (facing into the court), and the front bench (facing towards the dais).

The key variable impacting daylight performance was identified as the lantern screen, defining the following sensitivity tests:

Test	Revision Date	Variable – lantern screen	
1	1822	Screen present	
2	August 1823 ***as built***	Screen removed	

6.4.2 Annualised Illuminance Probability

Annualised illuminance probability was measured using the same method as for Dulwich Picture Gallery, see section 6.3.2. Annual lux-hours were not calculated for the Court of Chancery, because cumulated light exposure was not considered to of concern in a law court.

6.4.3 Sunlight Penetration

Sunlight penetration was assessed under the CIE Clear Sky model, against both tests. A single viewpoint (looking south towards the dais) was chosen to view the interior at three dates, over hourly intervals during opening hours. Hours of operation were assumed to be between 10:00 and 16:00 hours. The dates chosen were the summer and winter solstices (21 June, 21 December respectively) and the spring equinox (21 March), these dates being representative of the range of solar conditions over a year. The resultant images were processed following the same procedure used for Dulwich Picture Gallery, see section 6.3.3.

7 Results

Daylight Factor results are shown using either exponential or logarithmic scales. The advantage of these over a linear scale is that they more closely match human vision. Numeric scales are mapped to a perceptually based colour scale [52].

7.1 Dulwich Picture Gallery

The daylight performance was found to be very similar, and therefore the results for two galleries only (one single cube, and one double cube shape) are shown here for clarity. The results for the remaining galleries are displayed in Appendix I.

7.1.1 Daylight Performance

7.1.1.1 Test 1 Clerestory Design Proposal

Test	Revision Date	Variables		
		Wall colour	Glass type	Window type
1	July/October 1811	Dark mineral red	Clear	Clerestory

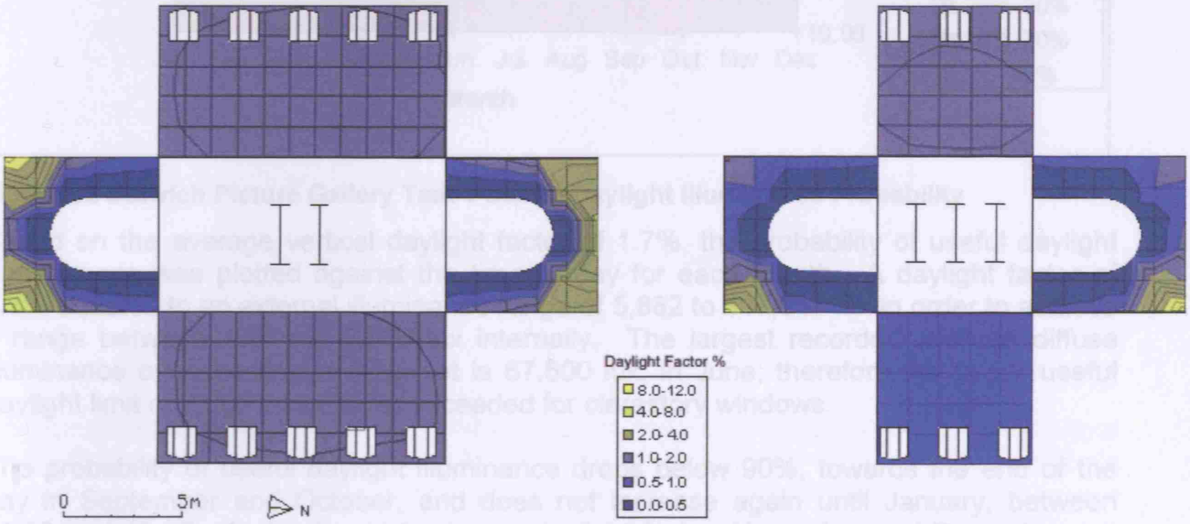


Figure 31 Dulwich Picture Gallery Test 1 Vertical Daylight Factors

	Maximum DF (%)	Minimum DF (%)	Average DF (%)
Gallery II	5.6	0.8	1.7
Gallery III	5.4	0.5	1.2
All Galleries	5.7	0.5	1.7

Clerestory windows were modelled in galleries II, III and IV only, as shown on the source drawing. Galleries I and V were lit using the octagonal lanterns with clear glass. Daylight is admitted through the clerestory windows, crosses the gallery and illuminates the opposite wall. The shading effect of the mausoleum to the west of gallery III can be clearly seen on the east wall and the west sides of the north and south walls. The clerestory windows show a uniform light distribution over the opposite walls, to the east and west.

The annual cumulative exposure for the maximum measured daylight factor of 5.7% was 3,060,443 lux-hours, between the hours of 10:00 and 16:00, 365 days a year (based on diffuse illuminance data only). The cumulative exposure calculated here is a minimum value, and will be higher using global illuminance data. Note that the maximum recommended cumulative exposure for oil painting is 600,000 lux-hours [53].

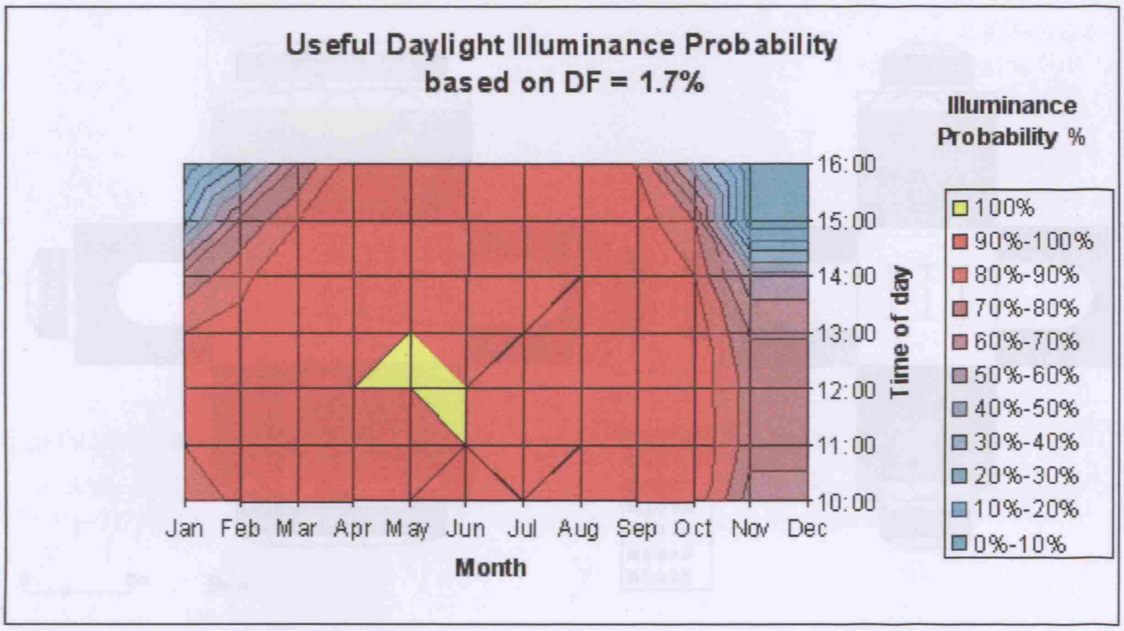


Figure 32 Dulwich Picture Gallery Test 1 Useful Daylight Illuminance Probability

Based on the average vertical daylight factor of 1.7%, the probability of useful daylight illuminances was plotted against the time of day for each month. A daylight factor of 1.7% equates to an external illuminance range of 5,882 to 117,647 lux in order to achieve a range between 100 and 2,000 lux internally. The largest recorded average diffuse illuminance over the annual data set is 67,500 lux, in June; therefore the upper useful daylight limit of 2,000 lux is never exceeded for clerestory windows.

The probability of useful daylight illuminance drops below 90%, towards the end of the day in September and October, and does not increase again until January, between 11:00 and 13:00. At this level of average daylight factor, November and December are very dark, peaking at 69% probability of useful daylight illuminance at midday.

7.1.1.2 Test 2 Gallery as Built

Test	Revision Date	Variables		
		Wall colour	Glass type	Window type
2	1815	Dark mineral red	Ground	Vertically glazed lantern

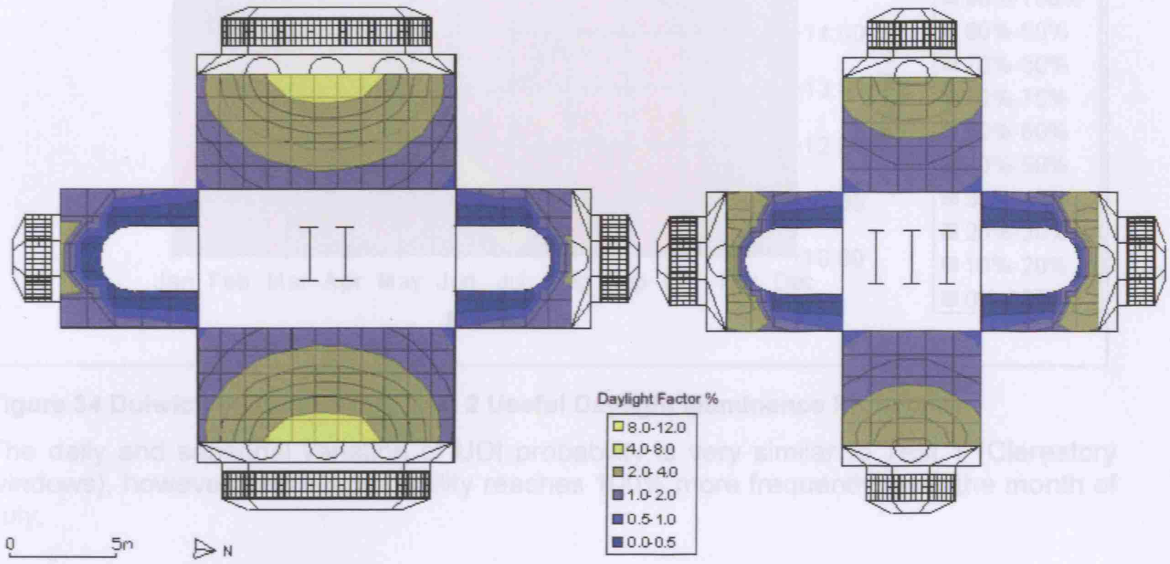


Figure 33 Dulwich Picture Gallery Test 2 Vertical Daylight Factors – As Built

	Maximum DF (%)	Minimum DF (%)	Average DF (%)
Gallery II	4.5	0.8	2.2
Gallery III	3.7	0.8	1.9
All Galleries	4.5	0.6	2.0

The lanterns admit light in a similar way to clerestory windows, illuminating the opposite wall. The south-facing wall of Gallery III is brighter than that of Gallery II, due to its smaller size; daylight penetrating the south side of the lantern in Gallery II cannot reach the length of the double-cube gallery. The east and west facing walls of Gallery II are more brightly illuminated because more daylight is admitted from the longer lantern sides facing in these directions.

The diffuse properties of ground glass were not modelled, therefore the daylight factors for this test case may be over-estimated.

The annual cumulative exposure for the maximum measured daylight factor of 4.5% was 2,324,569 lux-hours, between the hours of 10:00 and 16:00, 365 days a year (based on diffuse illuminance data only).

Based on the average vertical daylight factor of 2.0%, the probability of useful daylight illuminances was plotted against the time of day for each month. A daylight factor of 2.0% equates to an external illuminance range of 5,000 to 100,000 lux in order to achieve a range between 100 and 2,000 lux internally. The largest recorded average diffuse illuminance over the annual data set is 67,500 lux, in June; therefore the upper useful daylight limit of 2,000 lux is never exceeded for the design of the gallery as built.

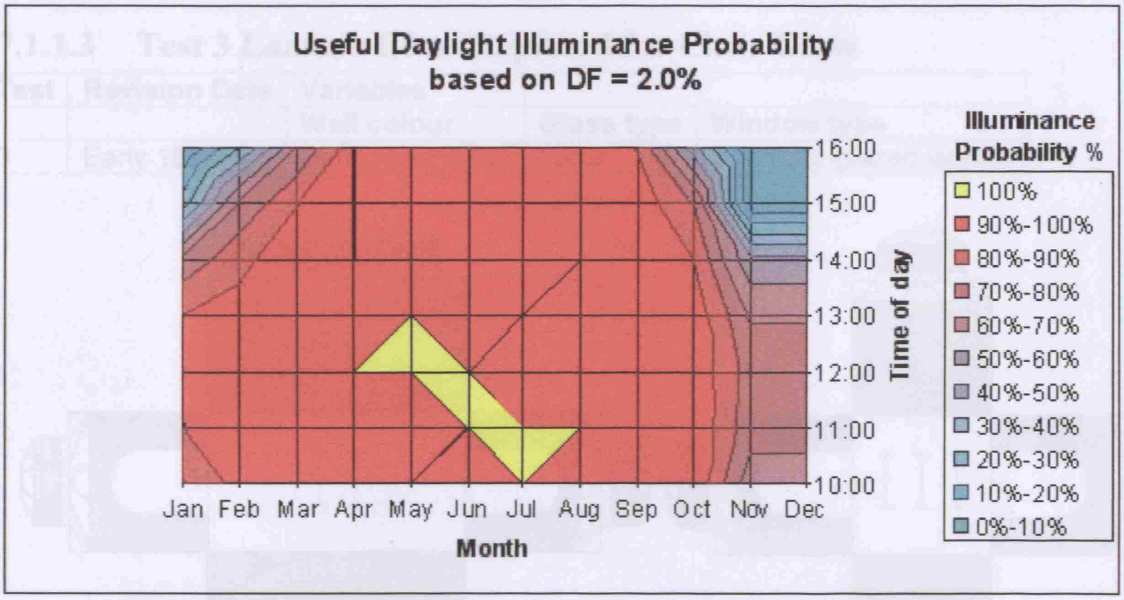


Figure 34 Dulwich Picture Gallery Test 2 Useful Daylight Illuminance Probability

The daily and seasonal variation of UDI probability is very similar to Test 1 (Clerestory windows), however the UDI probability reaches 100% more frequently, over the month of July.

7.1.1.3 Test 3 Lantern Glass Replaced for Clear Glass

Test	Revision Date	Variables		
		Wall colour	Glass type	Window type
3	Early 1829	Dark mineral red	Clear	Vertically glazed lantern

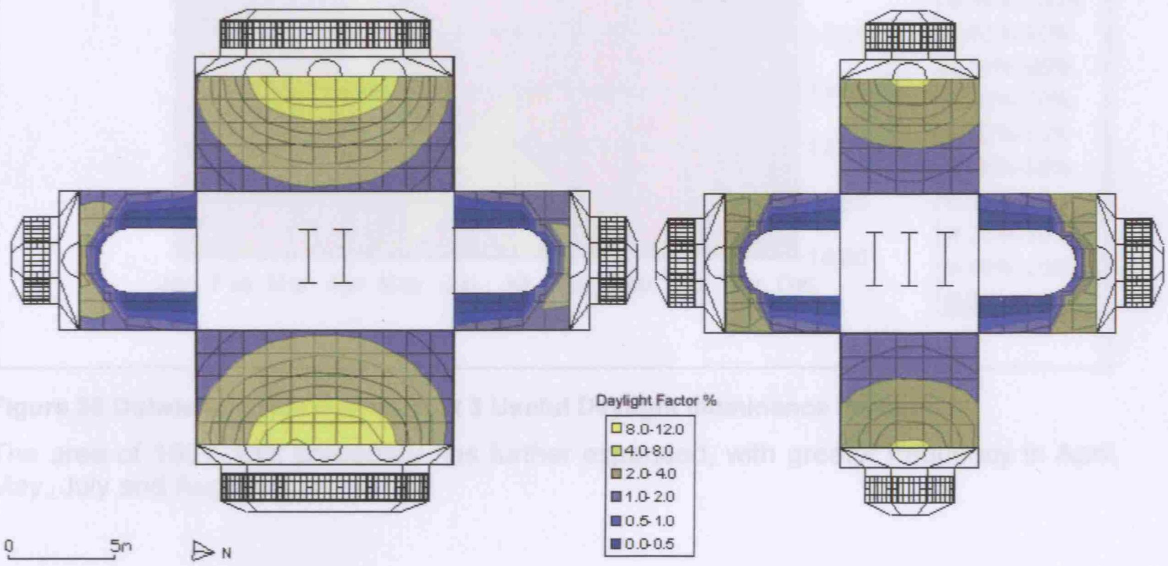


Figure 35 Dulwich Picture Gallery Test 3 Vertical Daylight Factors

	Maximum DF (%)	Minimum DF (%)	Average DF (%)
Gallery II	5.1	0.9	2.5
Gallery III	4.9	0.9	2.2
All Galleries	5.1	0.8	2.3

The characteristic illumination pattern from the lantern can still be seen, now with greater intensity due to the higher glass transmission. On the east and west walls, most of the hanging space (up to height 3.35m) now has daylight factors in excess of 2.0%. The north and south remain poorly lit, with daylight factors predominantly below 2.0%.

The annual cumulative exposure for the maximum measured daylight factor of 5.1% was 2,657,209 lux-hours, between the hours of 10:00 and 16:00, 365 days a year (based on diffuse illuminance data only).

Based on the average vertical daylight factor of 2.3%, the probability of useful daylight illuminances was plotted against the time of day for each month. A daylight factor of 2.0% equates to an external illuminance range of 4,348 to 86,957 lux in order to achieve a range between 100 and 2,000 lux internally. The largest recorded average diffuse illuminance over the annual data set is 67,500 lux, in June; therefore the upper useful daylight limit of 2,000 lux is never exceeded for the gallery with clear glass lanterns.

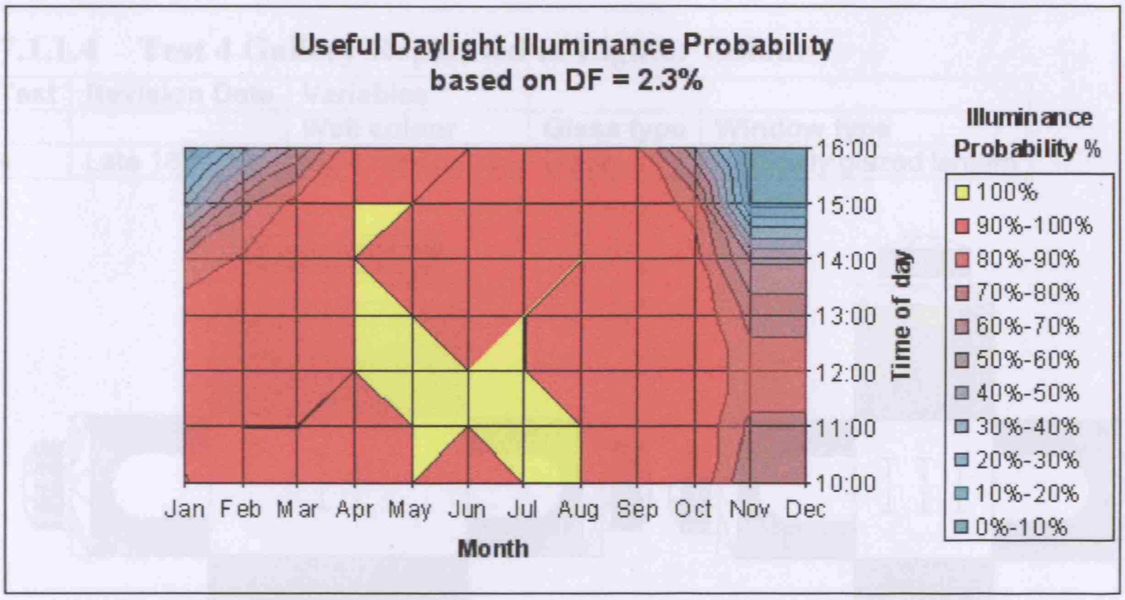


Figure 36 Dulwich Picture Gallery Test 3 Useful Daylight Illuminance Probability

The area of 100% UDI probability has further expanded, with greater frequency in April, May, July and August.

7.1.1.4 Test 4 Gallery Repainted in Lighter Colour

Test	Revision Date	Variables		
		Wall colour	Glass type	Window type
4	Late 1829	Light mineral red	Clear	Vertically glazed lantern

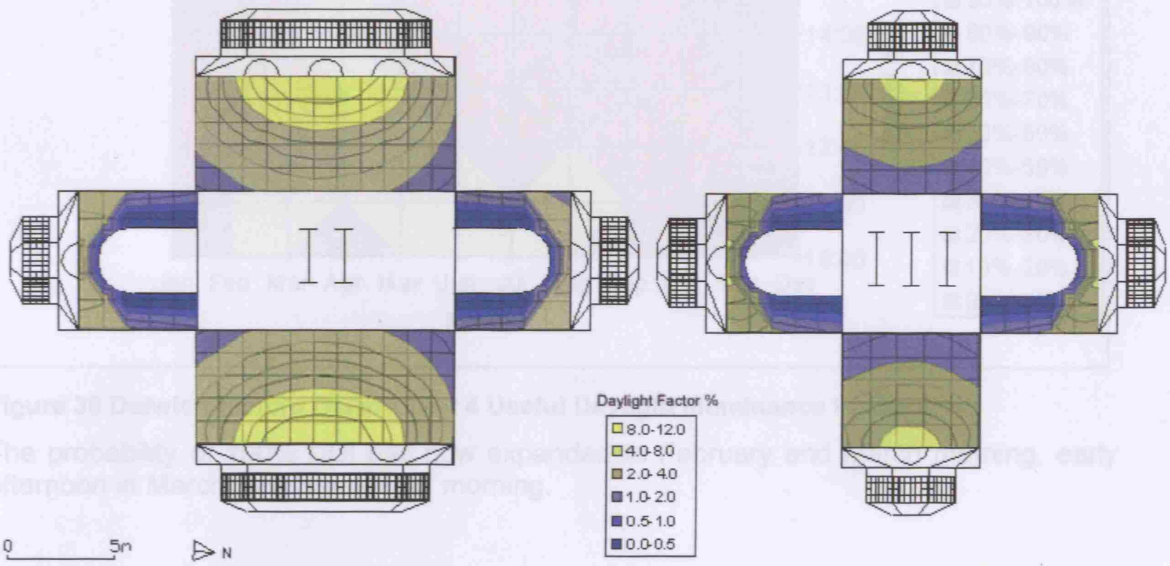


Figure 37 Dulwich Picture Gallery Test 4 Vertical Daylight Factors

	Maximum DF (%)	Minimum DF (%)	Average DF (%)
Gallery II	5.5	1.2	2.9
Gallery III	4.5	1.2	2.5
All Galleries	5.5	1.2	2.7

The effect of the higher wall reflectance can be seen in the expansion of the 2.0 to 4.0% daylight factor zone down to floor level in the larger gallery, and the 4.0 to 8.0% daylight factor zone expanding to a greater area of the east and west walls. The impact of the higher reflectance is greatest in the smaller gallery. The main hanging space on the north and south walls remains lit at below 2.0% daylight factor in both galleries.

The annual cumulative exposure for the maximum measured daylight factor of 5.5% was 2,850,666 lux-hours, between the hours of 10:00 and 16:00, 365 days a year (based on diffuse illuminance data only).

Based on the average vertical daylight factor of 2.7%, the probability of useful daylight illuminances was plotted against the time of day for each month. A daylight factor of 2.0% equates to an external illuminance range of 3,704 to 74,074 lux in order to achieve a range between 100 and 2,000 lux internally. The largest recorded average diffuse illuminance over the annual data set is 67,500 lux, in June; therefore the upper useful daylight limit of 2,000 lux is never exceeded for the gallery repainted in a lighter colour.

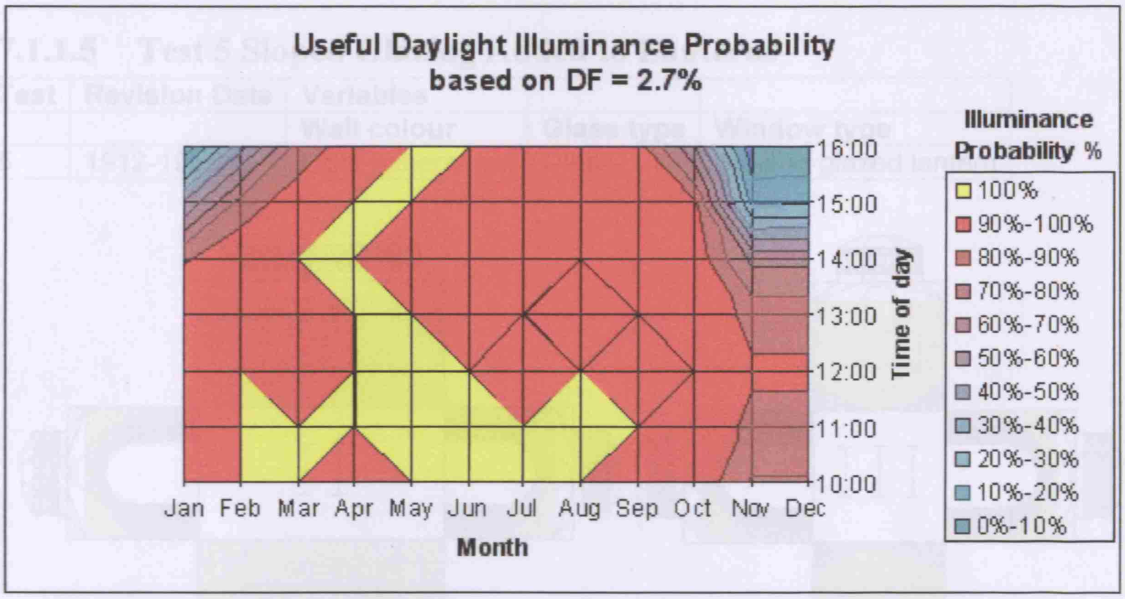


Figure 38 Dulwich Picture Gallery Test 4 Useful Daylight Illuminance Probability

The probability of 100% UDI has now expanded to February and March morning, early afternoon in March, and September morning.

7.1.1.5 Test 5 Sloped Glazing Added to Lanterns

Test	Revision Date	Variables		
		Wall colour	Glass type	Window type
5	1912-1915	Light mineral red	Clear	Sloping glazed lantern

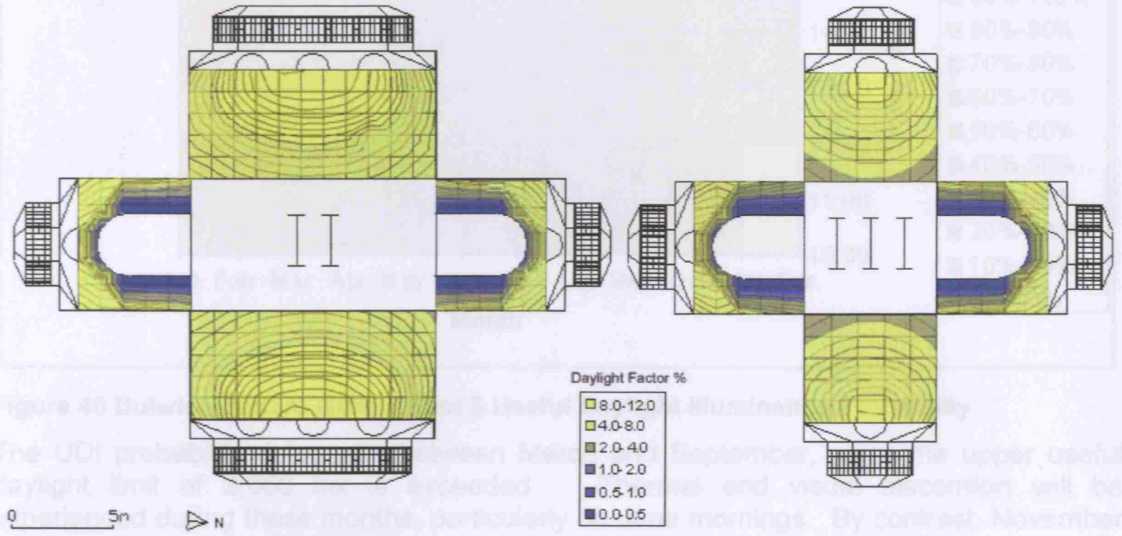


Figure 39 Dulwich Picture Gallery Test 5 Vertical Daylight Factors

	Maximum DF (%)	Minimum DF (%)	Average DF (%)
Gallery II	11.6	3.7	7.2
Gallery III	8.6	3.0	5.4
All Galleries	11.7	2.9	6.3

Glazing the sloped surface of the lanterns has a marked effect on the amount of light entering the galleries. Nearly half the east and west wall areas in gallery II now have daylight factors greater than 8.0%, while the majority of the east and west walls in the smaller gallery III have daylight factors between 4.0 and 8.0%. The north and south walls in both galleries have daylight factors of at least 3.0%.

The annual cumulative exposure for the maximum measured daylight factor of 11.7% was 6,075,872 lux-hours, between the hours of 10:00 and 16:00, 365 days a year (based on diffuse illuminance data only). This figure is at least double that of the other tests and ten times the recommended level for conservation of oil paintings.

Based on the average vertical daylight factor of 6.3%, the probability of useful daylight illuminances was plotted against the time of day for each month. A daylight factor of 6.3% equates to an external illuminance range of 1,587 to 31,746 lux in order to achieve a range between 100 and 2,000 lux internally. The largest recorded average diffuse illuminance over the annual data set is 67,500 lux, in June; therefore the upper useful daylight limit of 2,000 lux is exceeded with the sloped lanterns.

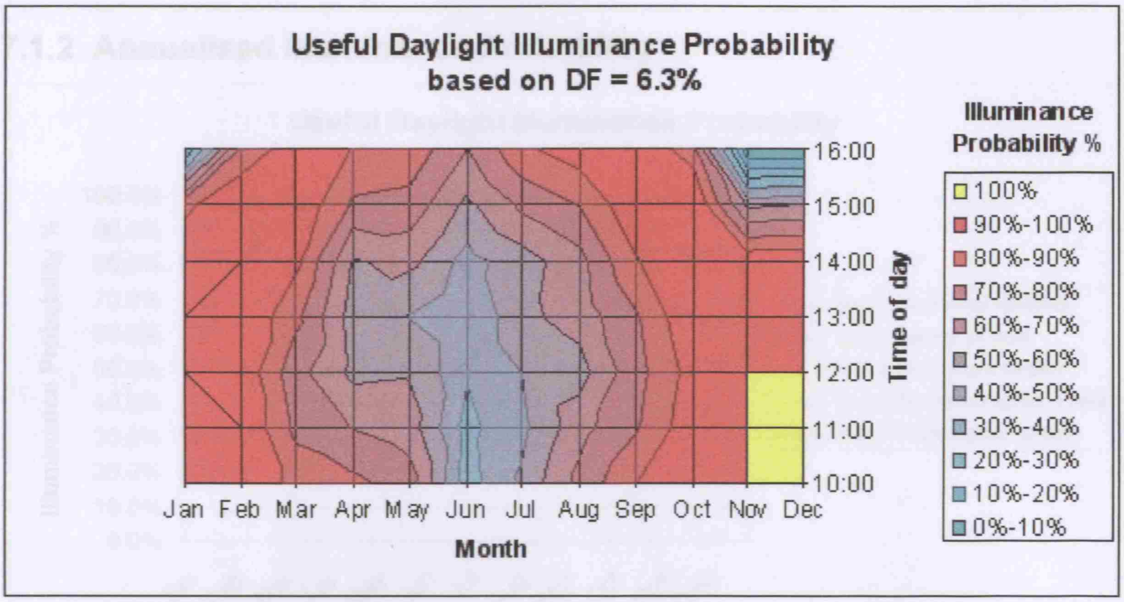


Figure 40 Dulwich Picture Gallery Test 5 Useful Daylight Illuminance Probability

The UDI probability decreases between March and September, when the upper useful daylight limit of 2,000 lux is exceeded. Thermal and visual discomfort will be experienced during these months, particularly on June mornings. By contrast, November and December mornings reach 100% probability of UDI, but this drops off rapidly from 14:00 onwards.

7.1.1.6 Test 7 Indirect Daylight Component

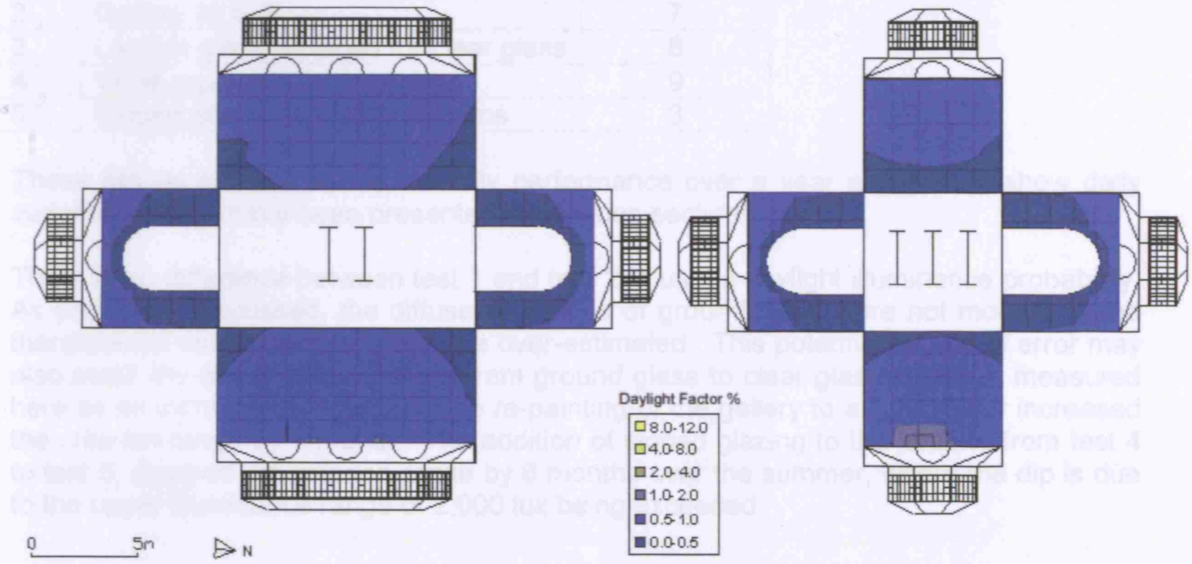


Figure 41 Dulwich Picture Gallery Test 7 Indirect Daylight Component

Based on test 2, daylight factors were measured with all surface reflectances set to zero, in order to quantify the direct daylight component. The resultant daylight factors were subtracted from the total daylight factor at each measured point, in order to obtain the indirect daylight factor component.

7.1.2 Annualised Illuminance Probability

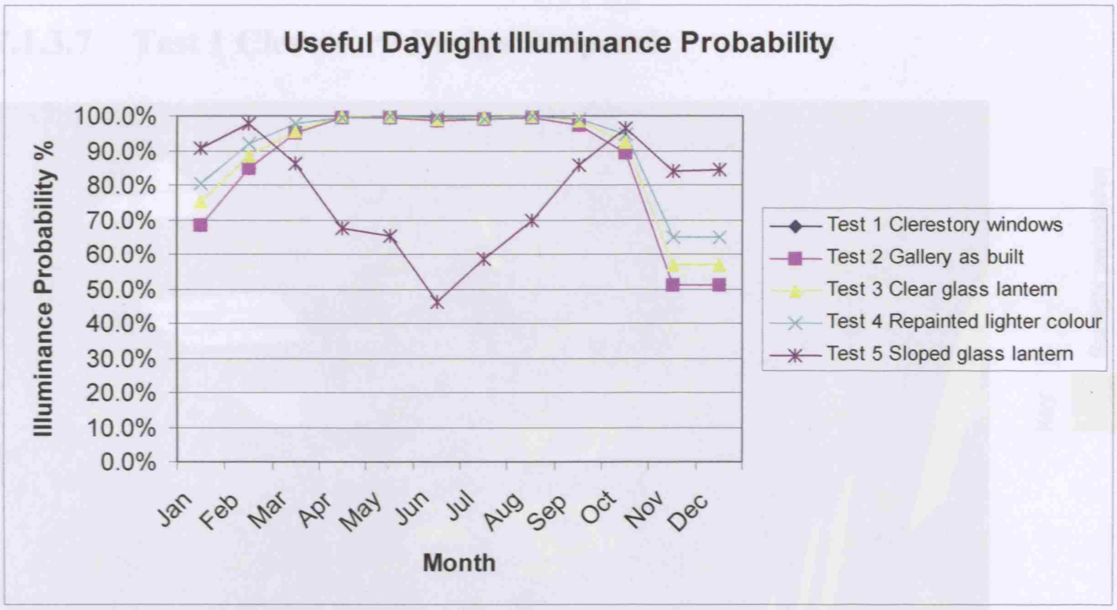


Figure 42 Dulwich Picture Gallery Comparison of Useful Daylight Illuminance Probability

An acceptability criterion of 90% was set for the probability that daylight within the space will be within the useful range 100 - 2,000 lux. Using this criterion, the annual performance was summarised as follows:

Test	Description	Months/Year criterion met
1	Clerestory design proposal	7
2	Gallery as built	7
3	Lantern glass replaced for clear glass	8
4	Walls repainted lighter colour	9
5	Sloped glazing added to lanterns	3

These results summarise the monthly performance over a year and do not show daily variations, which have been presented in previous sections.

There is no difference between test 1 and test 2 in useful daylight illuminance probability. As previously discussed, the diffuse properties of ground glass were not modelled, and therefore the results for test 2 may be over-estimated. This potential source of error may also mask the effect of the change from ground glass to clear glass in test 3, measured here as an increase of 1 month. The re-painting of the gallery to a light colour increased the criterion range by 1 month. The addition of sloped glazing to the lantern, from test 4 to test 5, dropped the criterion range by 6 months over the summer, where the dip is due to the upper illuminance range of 2,000 lux being exceeded.

7.1.3 Sunlight Penetration

7.1.3.7 Test 1 Clerestory Design Proposal

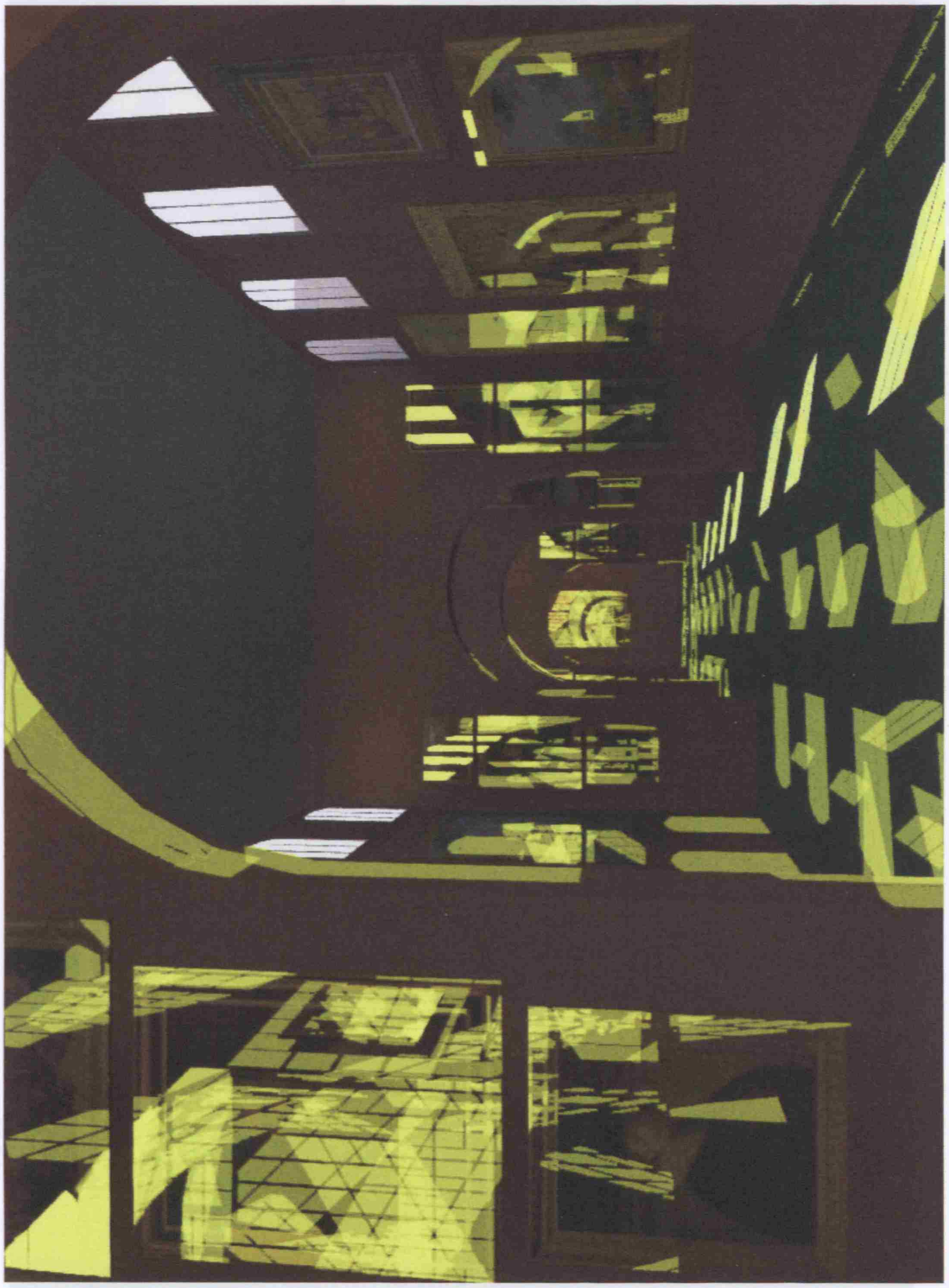


Figure 43 Dulwich Picture Gallery Test 1 Sunlight Penetration

7.1.3.8 Test 2 Gallery as Built

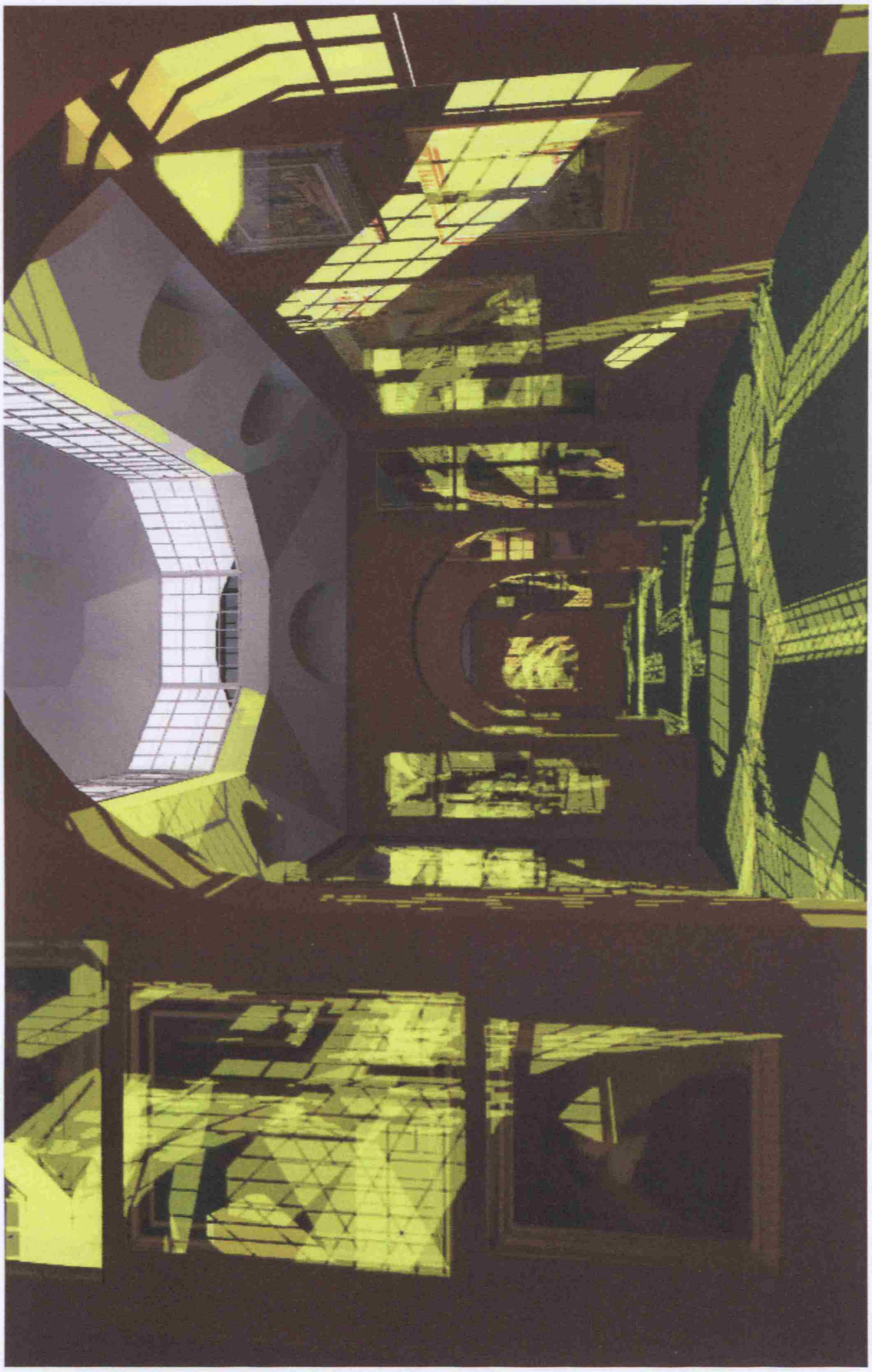
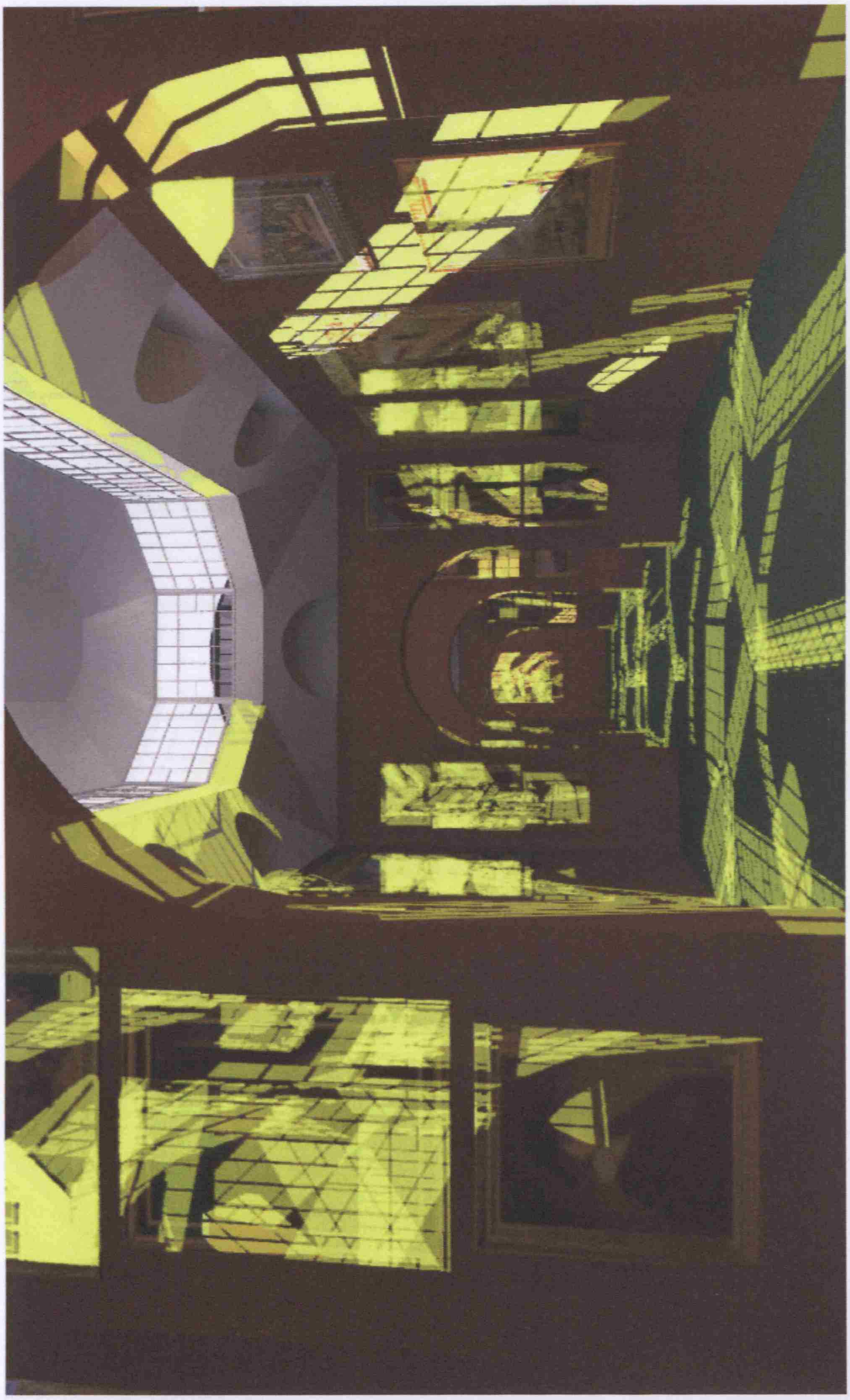


Figure 44 Dulwich Picture Gallery Test 2 Sunlight Penetration

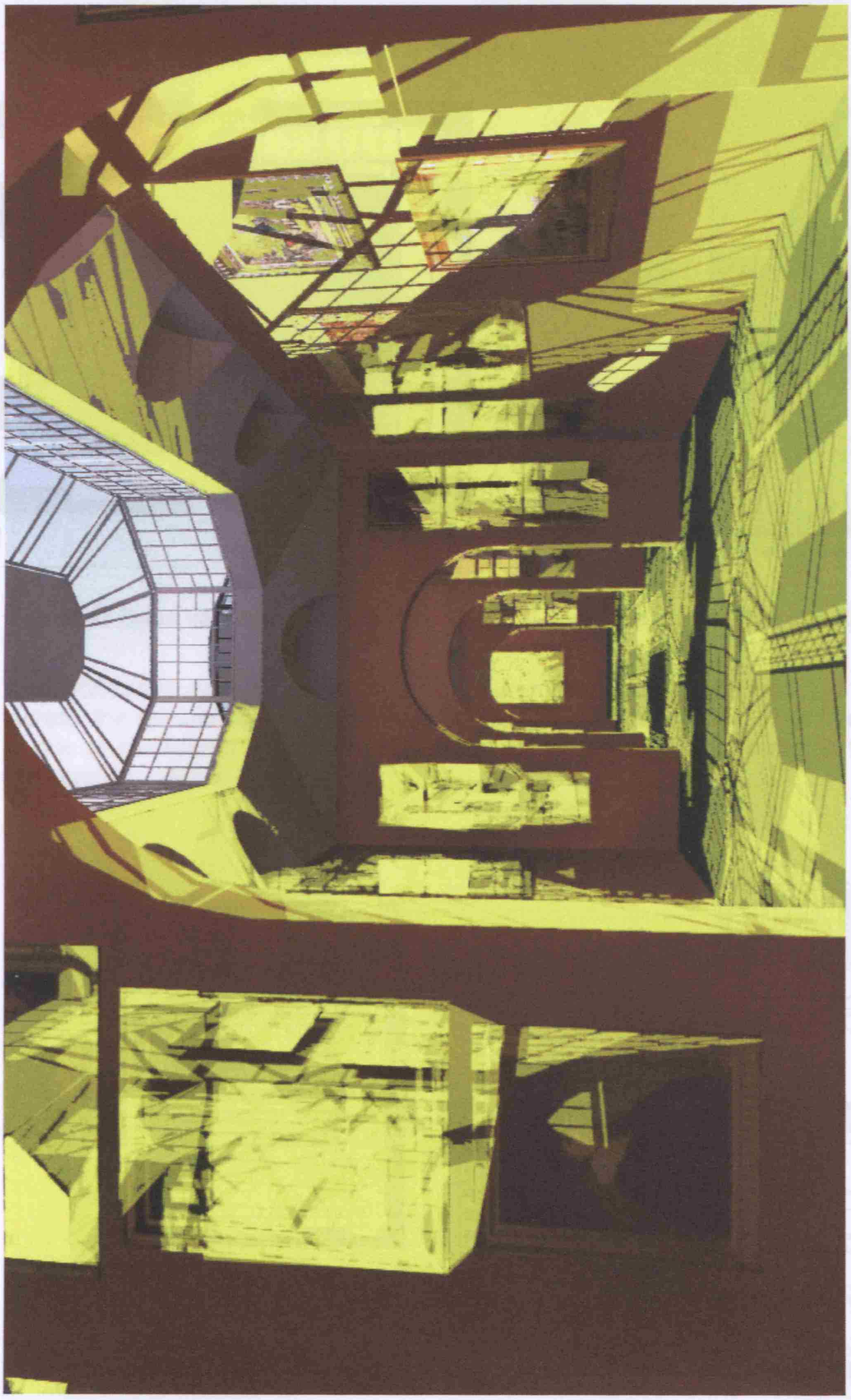
7.1.3.9 Test 3 Lantern Glass Replaced for Clear Glass



Key:
Sunlight penetration

Figure 45 Dulwich Picture Gallery Test 3 Sunlight Penetration

7.1.3.10 Test 5 Sloped Glazing Added to Lanterns



Key: Sunlight penetration

Figure 46 Dulwich Picture Gallery Test 5 Sunlight Penetration

7.2 Court of Chancery

7.2.1 Daylight Performance

7.2.1.11 Test 1 With Lantern Screen

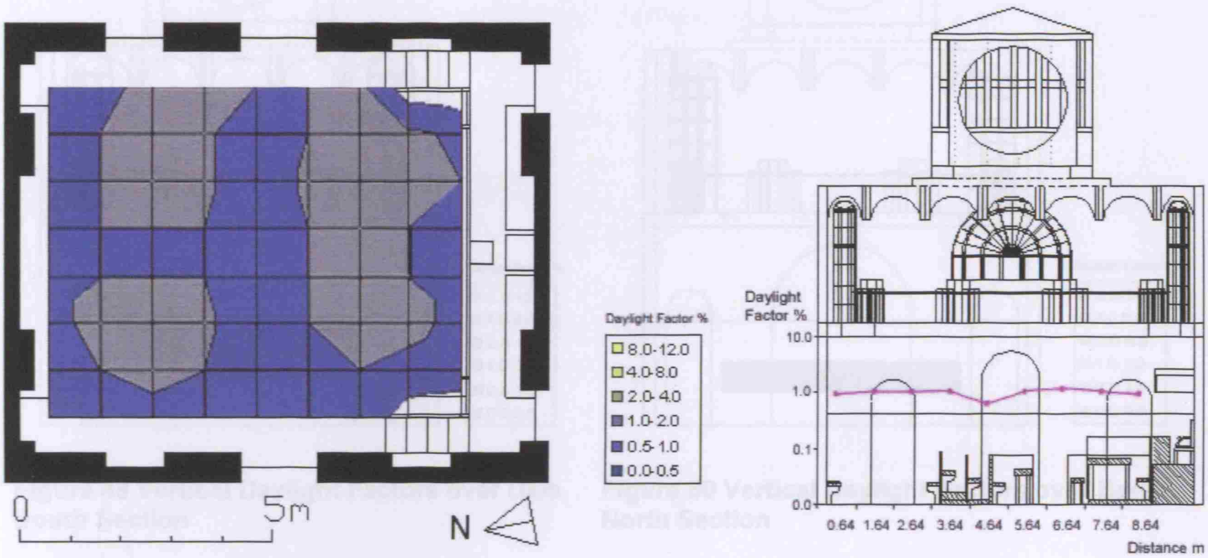


Figure 47 Court of Chancery Horizontal Daylight Factors at 1.1m, Plan and East Section

The horizontal daylight factors at a measurement plane height of 1.1m are evenly low across the ground floor, with a maximum daylight factor of 1.1%. The very slight pattern is due to shadowing from the gallery at the sides, the solid lantern roof in the middle, and Westminster Hall to the east.

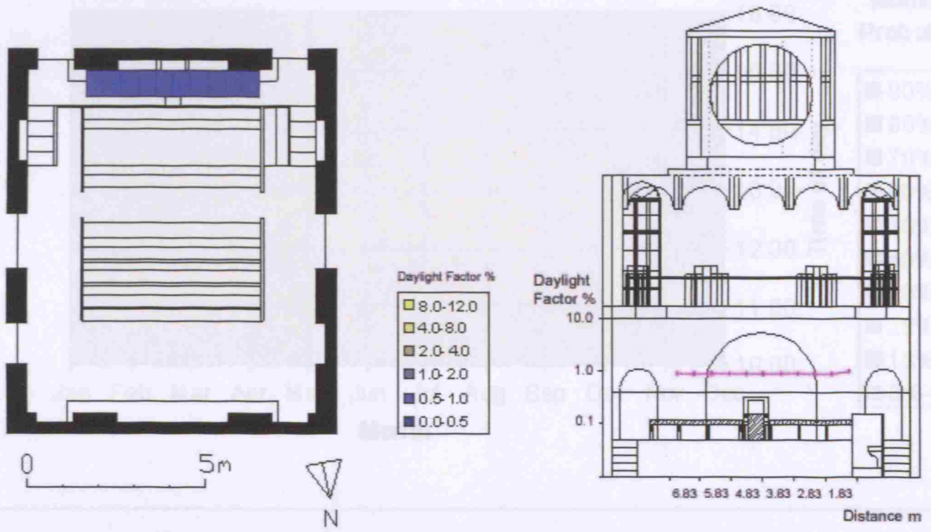


Figure 48 Court of Chancery Horizontal Daylight Factors at 1.85m, Plan and South Section

The horizontal daylight factors at a measurement plane height of 1.85m are evenly low across the dais, with a maximum daylight factor of 1.0%.

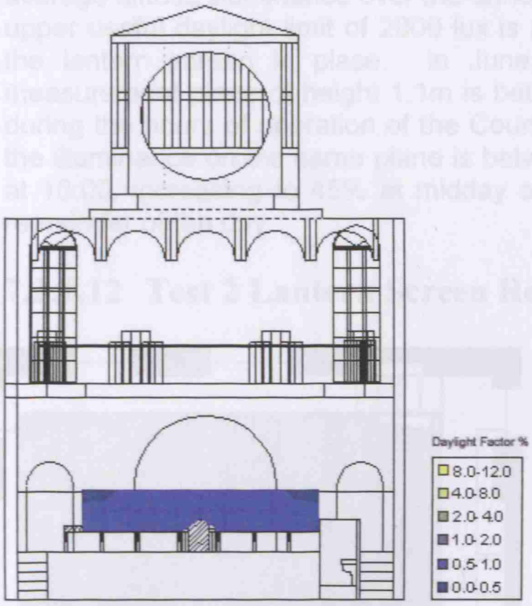


Figure 49 Vertical Daylight Factors over Dais, South Section

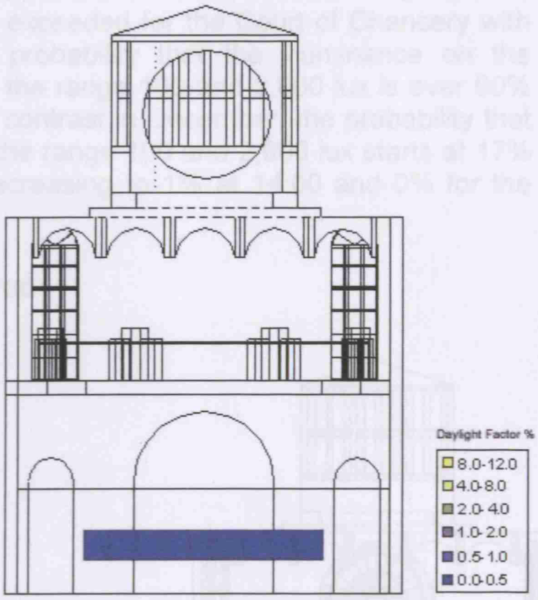


Figure 50 Vertical Daylight Factors over Bench, North Section

The vertical daylight factors on vertical measurement planes over the dais and the front bench are again evenly low. Maximum daylight factors are 0.8% over the dais and 0.3% over the bench. The slight dip in daylight factor over the dais in the top corners is due to shadowing from the tribunal canopy.

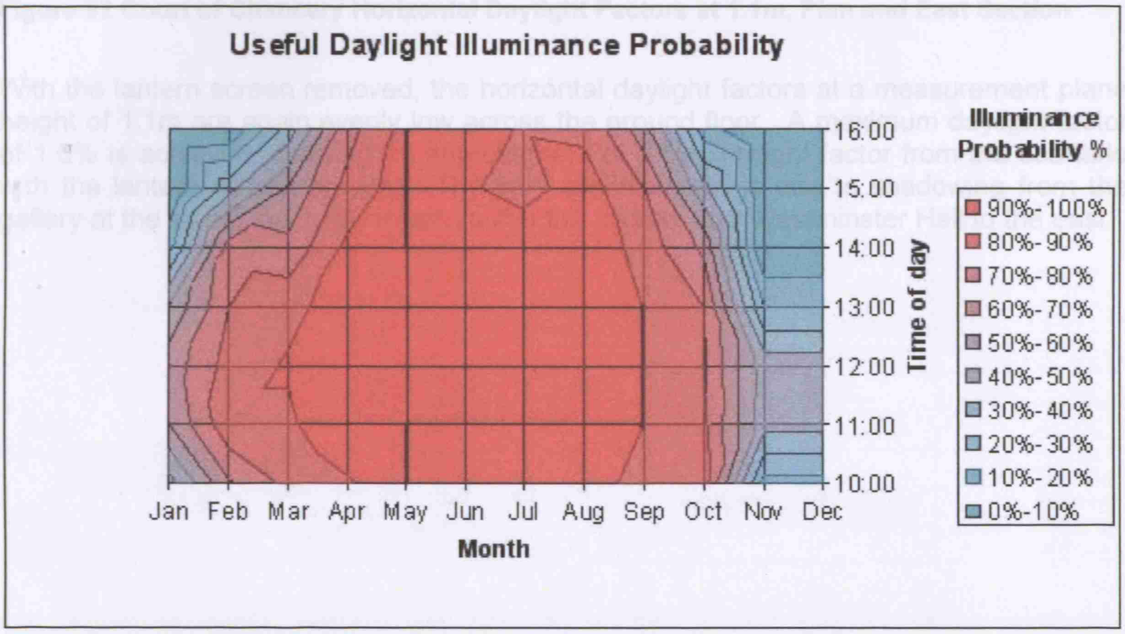


Figure 51 Court of Chancery Diffuse Test 1 Useful Daylight Illuminance Probability

Based on the average daylight factor of 0.9% on the horizontal plan at height 1.1m, the probability of daylight illuminances was plotted against the time of day for each month. A daylight factor of 0.9% equates to an external illuminance range of 11,111 to 222,222 lux in order to achieve a range between 100 and 2000 lux internally. The largest recorded average diffuse illuminance over the annual data set is 67,500 lux, in June. Therefore the upper useful daylight limit of 2000 lux is never exceeded for the Court of Chancery with the lantern screen in place. In June, the probability that the illuminance on the measurement plane of height 1.1m is between the range 100 and 2,000 lux is over 90% during the hours of operation of the Court. By contrast in December, the probability that the illuminance on the same plane is between the range 100 and 2,000 lux starts at 17% at 10:00, increasing to 45% at midday and decreasing to 1% at 14:00 and 0% for the remainder of the day.

7.2.1.12 Test 2 Lantern Screen Removed

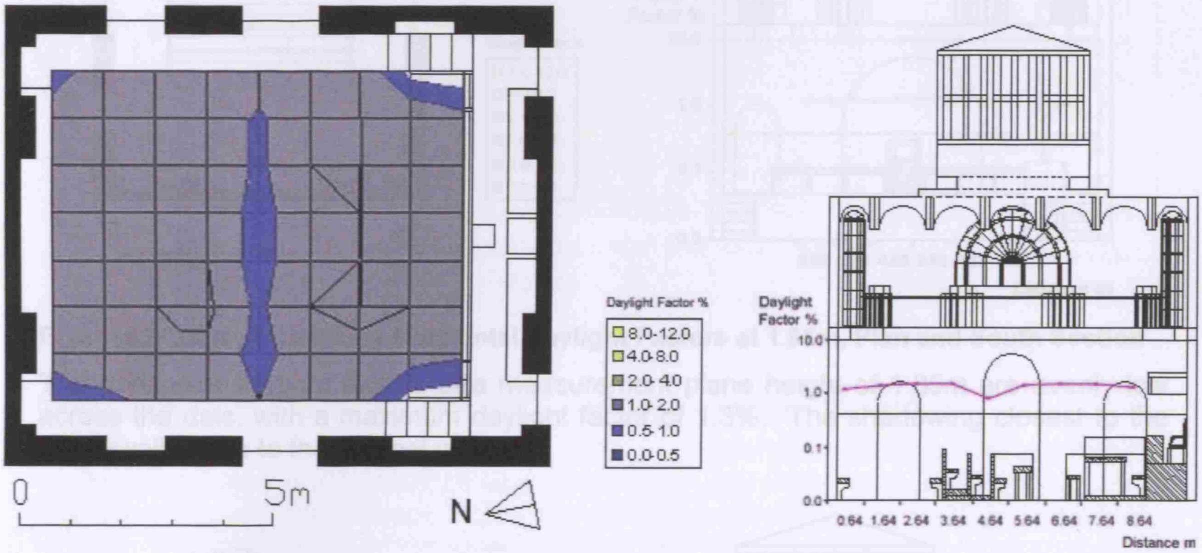


Figure 52 Court of Chancery Horizontal Daylight Factors at 1.1m, Plan and East Section

With the lantern screen removed, the horizontal daylight factors at a measurement plane height of 1.1m are again evenly low across the ground floor. A maximum daylight factor of 1.6% is achieved, showing an improvement of 0.5% daylight factor from the scenario with the lantern screen present. The very slight pattern is due to shadowing from the gallery at the sides, the solid lantern roof in the middle, and Westminster Hall to the east.

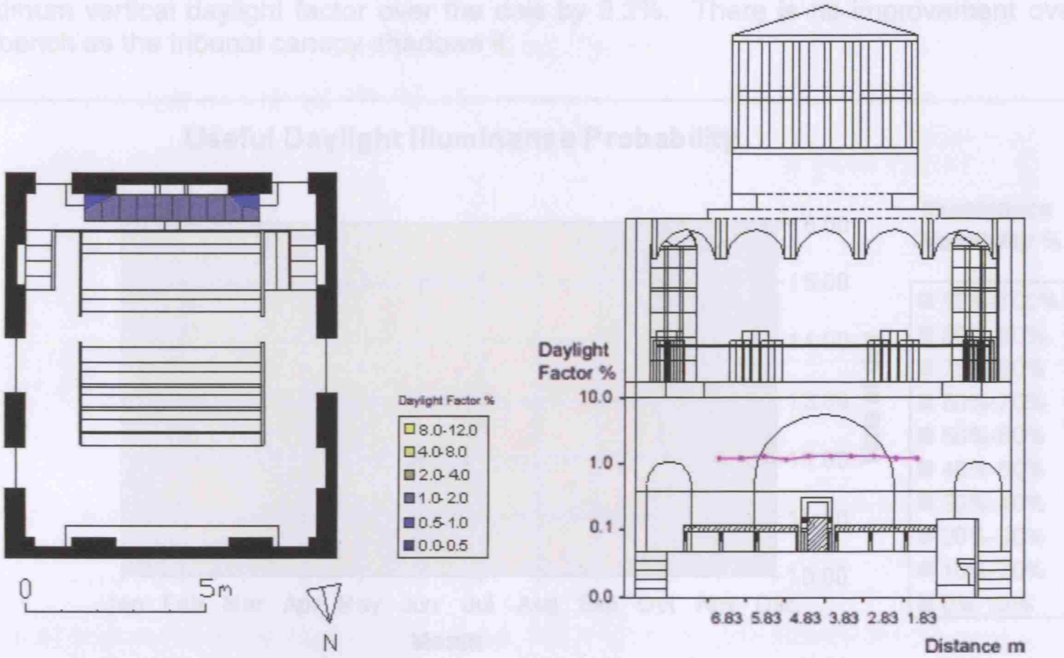


Figure 53 Court of Chancery Horizontal Daylight Factors at 1.85m, Plan and South Section

The horizontal daylight factors at a measurement plane height of 1.85m are evenly low across the dais, with a maximum daylight factor of 1.3%. The shadowing closest to the south wall is due to the tribunal canopy.

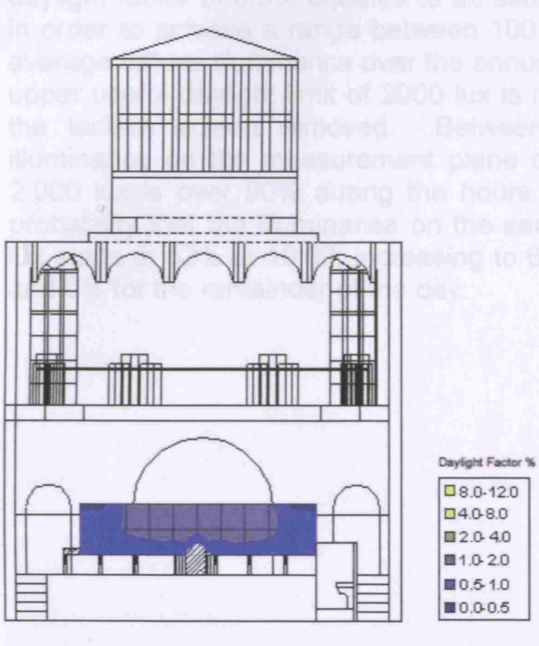


Figure 54 Vertical Daylight Factors over Dais, South Section

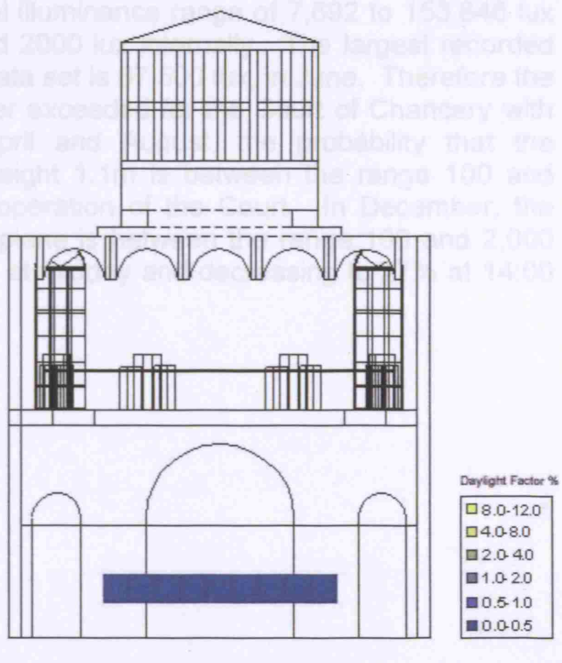


Figure 55 Vertical Daylight Factors over Bench, North Section

The vertical daylight factors on vertical measurement planes over the dais and the front bench are again evenly low. Maximum daylight factors are 1.1% over the dais and 0.3% over the bench. The slight dip in daylight factor over the dais in the top corners is due to shadowing from the tribunal canopy. The removal of the lantern screen has improved the maximum vertical daylight factor over the dais by 0.3%. There is no improvement over the bench as the tribunal canopy shadows it.

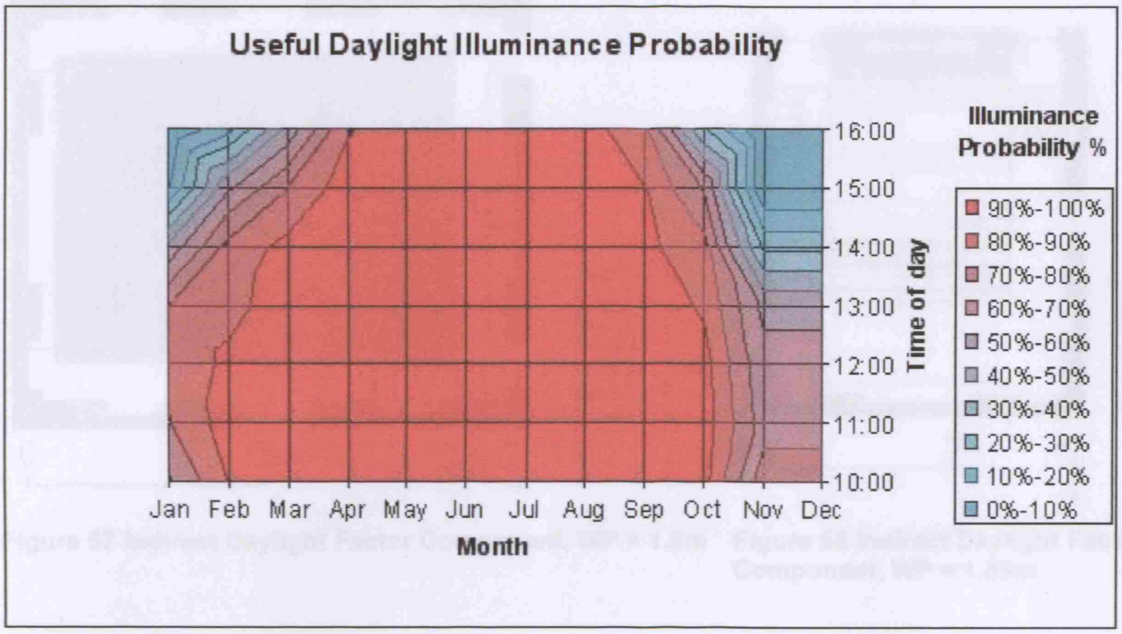


Figure 56 Court of Chancery Test 2 Useful Daylight Illuminance Probability

Based on the average daylight factor of 1.3% on the horizontal plan at height 1.1m, the probability of daylight illuminances was plotted against the time of day for each month. A daylight factor of 0.9% equates to an external illuminance range of 7,692 to 153,846 lux in order to achieve a range between 100 and 2000 lux internally. The largest recorded average diffuse illuminance over the annual data set is 67,500 lux, in June. Therefore the upper useful daylight limit of 2000 lux is never exceeded for the Court of Chancery with the lantern screen removed. Between April and August, the probability that the illuminance on the measurement plane of height 1.1m is between the range 100 and 2,000 lux is over 90% during the hours of operation of the Court. In December, the probability that the illuminance on the same plane is between the range 100 and 2,000 lux starts at 53% at 10:00, increasing to 63% at midday and decreasing to 27% at 14:00 and 0% for the remainder of the day.

7.2.1.13 Test 3 Indirect Daylight Component

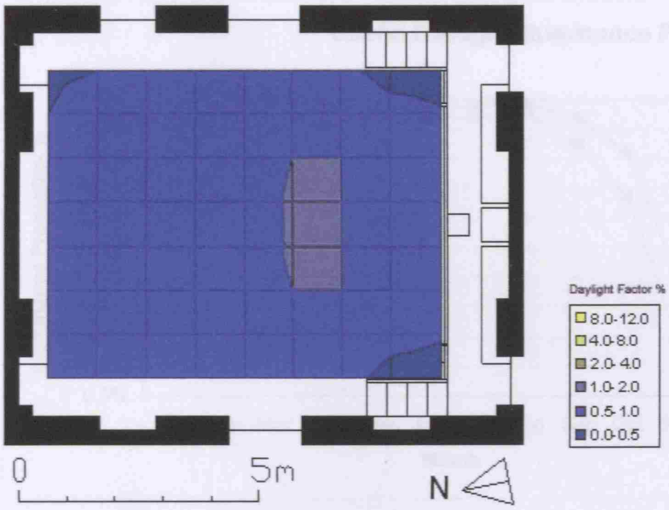


Figure 57 Indirect Daylight Factor Component, WP = 1.8m

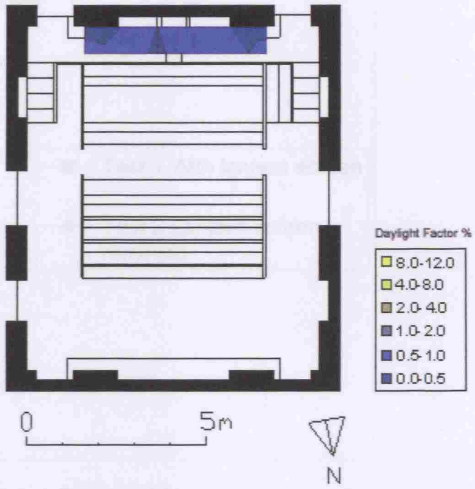


Figure 58 Indirect Daylight Factor Component, WP = 1.85m

Daylight factors were measured with all surface reflectances set to zero, in order to quantify the direct daylight component. The resultant daylight factors were subtracted from the total daylight factor at each measured point, in order to obtain the indirect daylight factor component.

7.2.2 Annualised Illuminance Probability

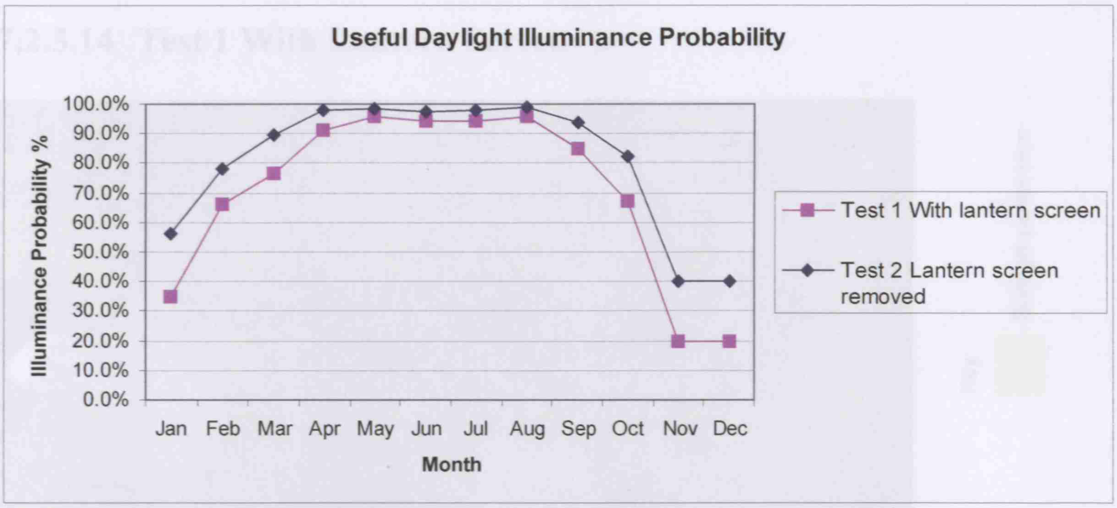


Figure 59 Court of Chancery Comparison of Daylight Illuminance Probability

Using the defined threshold value of 90%, the annual performance from Figure 51 Court of Chancery Diffuse Test 1 Useful Daylight Illuminance Probabilit and Figure 56 Court of Chancery Test 2 Useful Daylight Illuminance Probability was summarised as follows:

Test	Description	Months/Year threshold exceeded
1	With Lantern Screen	6
2	Lantern Screen Removed	7

7.2.3 Sunlight Penetration

7.2.3.14 Test 1 With Lantern Screen

Key:

Sunlight penetration

Figure 60 Court of Chancery Test 1 With Lantern Screen

7.2.3.15 Test 2 Lantern Screen Removed

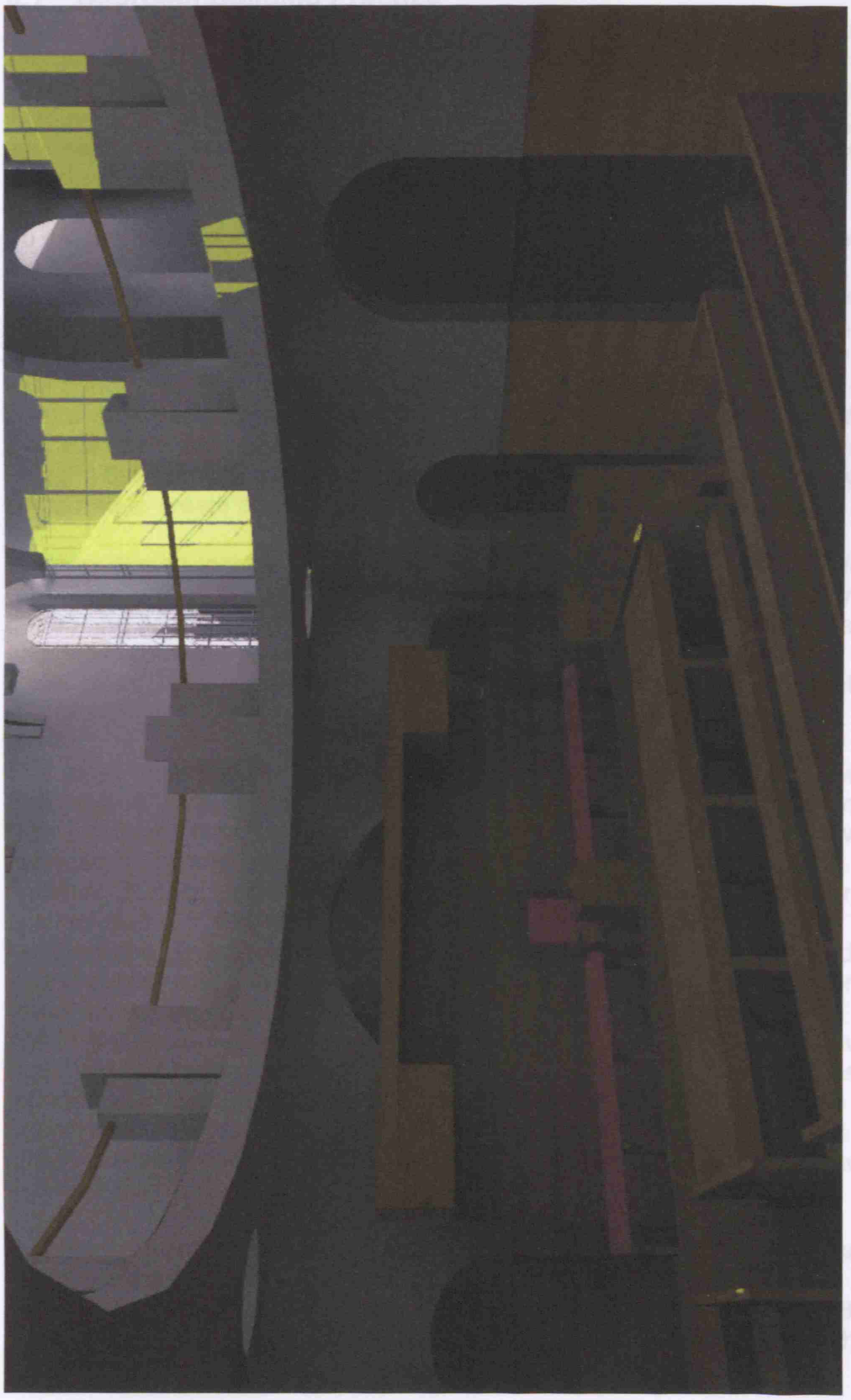


Figure 61 Court of Chancery Test 2 Lantern Screen Removed

8 Discussion

8.1 Georgian Building Practice

Soane designed buildings for England's cool temperate climate, where the focus of window design is on admission of natural light rather than solar gain control in sunnier climates. How did Soane, and others in the construction trade, decide the appropriate window area to provide sufficient light? Advice published in the eighteenth century suggested that a window area equal to the square root of the cubic volume of a room would provide the required amount of light [54].

To set this window area formula in context, we must consider whether the Georgians had the same view of daylight adequacy as we do in the twenty-first century. At night, rooms were typically lit with only one or two light sources: by day, daylight was not routinely supplemented with artificial sources, as is common today. Human eye-brain physiology has not evolved in the last two hundred years; we are able to see over a wide range of light conditions, from near darkness through to bright sunlight. Eyesight deteriorates with age; a sixty-year old receives a third of the amount of light as a twenty-year old. The average life expectancy in Georgian times was 37 years, compared with 80 years and rising in this century. Our ageing population, and the advent of electric lighting, may have combined to create an expectation for greater average light levels as the norm.

Window design includes the glazing as well as the size of opening. We know from the refurbishment of the Soane Museum that Soane used a wide variety of glass types, depending on the function of the room and the desired effect. Crown glass, the cheapest and most common glass available, was used in the servants' quarters, while expensive sheet glass, initially reserved for shop windows and palaces[7], was installed in the library [56].

The three main processes for making window glass were cylinder, crown and sheet (or plate) glass, in ascending order of quality. To make cylinder glass, molten glass was blown into long bubbles, the ends removed, the resulting cylinder slit down its length and flattened. Cylinder glass was cloudy from impurities picked up during contact with the flattening surface. For crown glass, the molten glass was blown into large globes of the desired diameter and transferred to a pontil rod opposite the blowpipe. The glassmaker removed the blowpipe, enlarging the resulting hole with a wooden paddle. The open-ended bubble was then spun on its pontil rod until the glass flashed open into a large flat disc, through centrifugal force. The resultant disc measured between 1.1m and 1.8m, and was cut into individual panes, squared or divided to maximise the available material. Resulting panes ranged in size from 0.44 to 0.29m, with around 10% loss. Crown glass retained its clarity, as it came into contact with no other material during its manufacture. Sheet glass was cast onto casting tables, cooled slowly then ground and polished. Sheet glass was very thick, in order to withstand the stress of grinding and polishing, and therefore very heavy. [57]

Cost was a key factor in the choice of construction materials in Georgian times, as now. Glass attracted duty between 1740 and 1845, this tax being raised in 1777 to help finance defence against the American Revolution, and again in 1812 to fund the Napoleonic Wars. Glass tax was based on weight[8], which encouraged the preference for crown glass [59].

[7] Wren's work at Hampton Court (1689-1694) [55]

[8] Window tax, enforced from 1696 to 1851, was an occupancy tax based on the number of windows in a building [58]. This tax would have been a client concern regarding ongoing costs, rather than an issue informing architect or builder material decisions.

8.2 *Dulwich Picture Gallery*

Dulwich College, the site of Dulwich Picture Gallery, was in the countryside in the early nineteenth century, away from the increasingly smoggy city of London. The large site meant few constraints on the orientation of the building; the main constraint was the budget. Soane's initial focus was on the overall site plan, and his ambition to build a new quadrangle to house the gallery, almshouses and mausoleum. The only obstruction was Dulwich College to the north. Although the quadrangle was not approved, Soane harboured his dream for many years and it seems that this master plan shaped the building into a long rectangle, in case it was ever executed [60]. The most effective orientation for lighting a rectangular building is for the long facades to face east west, and Soane quickly arrived at this conclusion.

8.2.1 Lantern design

The number of paintings in the Bourgeois Collection required maximum wall-space, necessitating a top-lighting solution. Soane explored a variety of lantern designs over a period of four months, culminating in an octagonal lantern with vertical glazing only. An octagonal shape was a good compromise between cost and performance: cheaper than circular lanterns and more responsive to daylight than square or rectangular. Soane's decision to use vertical glass only, rather than sloped must have been in response to the budget. Melinghof asserts that the vertically glazed lantern demonstrates Soane's awareness of picture lighting [61]: while Soane was certainly aware of the effects of top-lighting galleries [62], he used sloped glazing for the galleries at Fonthill and the Soane Museum. The small size of the windowpanes, commented on in a report of 1857 [63], also points to the limited budget.

Small panes mean a high proportion of fenestration to glass, thus reducing transmission. As modelled, the proportion of fenestration to glazing was 23.4% for the long octagonal lanterns, and 24.6% for the short octagonal lanterns. The eighteenth century formula for calculating the required window area was a rule of thumb, and did not take into account loss of window area due to fenestration.

		Window Area (m^2)		
	Room volume (m^3)	Estimated (using rule of thumb)	Actual (incl. fenestration)	Actual (excl. fenestration)
Gallery II	505.4	22.48	31.79	24.35
Gallery III	270.0	16.46	17.45	13.16

Soane might have thought that he had exceeded the window area rule of thumb, however exclusion of the fenestration from the window area shows a closer match for the double cube gallery and insufficient window area for the single cube gallery.

The performance of vertically glazed lanterns and lanterns with sloped and vertically glazing can be compared by looking at the results of tests 4 and 5. The distribution patterns on the walls are similar, but the sloping glazed lantern admits far more light. The average daylight factor is increased by 3.6% and the maximum daylight factor rises by 6.2% up to 11.7% with the sloping glazed lantern; a substantial change. By glazing the sloping surfaces of the lanterns the window surface area has been increased, and hence the total window surface in relation to the area of the room. The proportion of the window area to room area is defined as the glazing area, expressed as a percentage.

	Room area (m^2)	Window area (m^2) Vertical Lantern	Glazing Area (%) Vertical Lantern	Window area (m^2) Sloped Lantern	Glazing Area (%) Sloped Lantern
Gallery II	410.43	31.79	**7.75**	57.29	**13.96**
Gallery III	252.39	17.45	**6.91**	29.31	**11.61**

Fenestration between 4 and 10% is classified as medium, and between 10 and 25% as high. High fenestration can cause glare and thermal gain problems, and daylight control mechanisms are recommended to prevent these [64]. Richard Mather Architects have addressed these issues with their latest interventions at Dulwich, introducing double-glazing with automatically adjustable opaque blinds between the outer security glass and inner frosted panes [65].

8.2.2 Clerestory windows

Despite an early design decision to use top-lighting in the form of lanterns, Soane hesitated for over three months while he considered clerestory windows. Clerestory windows produce a more even distribution of light than top-lighting, on the east and west walls. The light distribution on the north and south walls, perpendicular to the clerestory windows, is similar to that achieved by top-lighting. The clerestory windows are placed close to the north south walls dividing the galleries, and so catch the light. Uniformity of light over the main display walls comes with a reduction in light levels of 1.1% average daylight factor (east and west walls only). Top-lighting shows a characteristic distribution pattern, concentrating on the tops of the walls and decreasing radially outwards.

		Window Area (m^2)		
	Room volume (m^3)	**Estimated (using rule of thumb)**	**Actual (incl. fenestration)**	**Actual (excl. fenestration)**
Gallery II	505.4	22.48	7.44	6.85
Gallery III	270.0	16.46	4.46	4.11

The measured area of the clerestory windows is only around a quarter of the window area recommended by the contemporary rule of thumb. This result may explain why Soane investigated larger 5-light windows and then finally abandoned clerestory windows in favour of top-lighting.

	Room area (m^2)	**Window area (m^2) Vertical Lantern**	**Glazing Area (%) Vertical Lantern**	**Window area (m^2) Clerestory Window**	**Glazing Area (%) Clerestory Window**
Gallery II	410.43	31.79	**7.75**	7.44	**1.81**
Gallery III	252.39	17.45	**6.91**	4.46	**1.77**

Glazing area between 1 and 4% is classified as low, and can produce very low light levels.

8.2.3 Glass type

No information was found for likely transmission values of the original ground glass, or the replacement clear glass. Assumptions were made that ground glass had a transmission value of 0.7, and clear glass 0.8 transmittance. The glass used was almost certainly crown glass for the reasons discussed earlier. Crown glass had a blue-green colour depending on its origin. No colour tint was modelled, as AGI32 does not take tint into account for radiosity calculations. Performance tests under the overcast sky showed the same distribution pattern, but the values increased from an average daylight factor value of 2.0% with ground glass to 2.3% for clear glass. The difference in daylight factor between the two glass types seems to be undervalued, and this could be due to the omission of diffuse properties in the definition of the ground glass material in the computer model.

8.2.4 Surface finishes

The only surface finish that Soane specified was the wall colour, a dark red recommended by the President of the Royal Academy. The Dulwich College Clerk of Works, George Tappen, took over from Soane in 1814. Tappen supervised the final fit-out, specifying green oilcloth for the floor. The impact of surface reflectance was investigated by measuring daylight performance of the gallery in the original dark red paint colour (reflectance 0.19), with the lighter red colour (reflectance 0.55) in which the gallery was repainted in 1829. Comparison between the two tests shows only a small increase of 0.4% in the average daylight factor for the lighter colour. An increase in daylight factor is to be expected, but given the relative surface area of the walls compared to the entire surface are of the gallery, a larger effect might have been anticipated. The potentially large impact of increasing the wall reflectance is masked by the paintings on the walls. Only 70 paintings were modelled, with reflectances ranging from 0.09 to 0.41. The actual number of paintings hung was far greater, at 360 and therefore any increase in wall reflectance would have minimal impact on overall daylight performance. A further effect of the paintings is that they would have been highly varnished, and therefore likely to cause veiling reflections when lit by direct daylight. More reflections would have been experienced from the upper rows of paintings than the lower. Gandy's rendering of the gallery shows the upper rows of paintings leaning forwards in order to minimise this unwanted effect.

8.2.5 Daylight control

It is not known whether blinds were installed at Dulwich Picture Gallery, although there is evidence at the Soane Museum that Soane did use blinds in his interiors. If blinds were installed at the gallery, they would only have been used to prevent glare (or perhaps retain heat at night) rather than for conservation purposes, as the degrading effects of light were unknown in the nineteenth century.

8.2.6 Daylight Performance

Current daylighting standards are an average daylight factor no less than 5% for interiors without supplementary artificial light, and an average daylight factor no less than 2% for interiors with supplementary artificial light. Artificial lighting was installed at Dulwich Picture Gallery only in 1974, and so if we judging the daylight performance of the gallery by today's standards we would expect an average daylight factor of at least 5% (ignoring conservation issues).

Soane's design proposal using clerestory windows (test 1) produced an average daylight factor of 1.7%, which is clearly inadequate in terms of daylighting. The design of the gallery as built (test 2) gave an average daylight factor of 2%, a slight improvement but still requiring supplementary artificial light by today's standards. Indeed, when the gallery was first open, visitors complained that the appearance of the gallery was too dark. In the UK, the typical overcast sky exceeds 5,000 lux 85% of the working day (09:00 to 17:30), which equates to 100 lux where the average daylight factor is 2%. While 100 lux has been assumed to be adequate for visual tasks in a picture gallery, this illuminance level may be too low for viewing paintings in detail.

The useful illuminance range considered here was between 100 and 2,000 lux. When considering the level of light required for viewing paintings, a range between 200 and 2,000 lux might have been more appropriate, as discussed above. Even so, from the useful daylight illuminance probability graphs, it can be seen that for test 1 to 4 that there would have been insufficient light in the winter months. As built, the gallery would have had illuminance levels below 100 lux at some time in the day between the months of October and February. From test 5 it can be seen that, without daylight controls, the sloped glazing lanterns provide an excess of light in the summer, likely to cause thermal and visual discomfort.

All versions of the gallery modelled here exceeded the recommended annual cumulative exposure for the conservation of oil paintings. In fact, the recommended exposure level of 600,000 lux-hours is only achievable with a daylight factor of less than 1.2% (diffuse illuminance only). This means that no gallery can be satisfactorily lit by daylight alone while also meeting conservation requirements; and supplementary electric lighting will be needed, particularly between the months of October and February.

8.2.7 Sunlight Penetration

Less sunlight penetration has been predicted for the clerestory windows (test 1), than the clear glass lantern (test 3), due to the smaller glazing area. As expected, there is no difference between the sunlight penetration observed for tests 2 (as built) and 3 (ground glass replaced by clear), due to the difference of only 10% in transmission and the diffuse properties of the ground glass not modelled. The introduction of sloped glazing in the lantern (test 5) increased the sunlight penetration significantly, on the walls and the floor. The pattern of sunlight with the sloping glazed lantern extends to the lower parts of the walls and almost the entire floor area.

Sunlight penetration predictions have shown pleasing patterns on the walls and floor, but direct sunlight on the walls leads to veiling reflections from the highly varnished surfaces of the paintings. Too much sunlight on the floor, as in the case of the sloped glazing lantern of test 5, also has disadvantages with the potential of excessive thermal gain. Modern conservation requirements do not allow direct sunlight on exhibits sensitive to light, such as oil paintings. Today's architects and lighting designers have taken this to extremes, designing daylit galleries with the dynamic aspect of daylight "designed" out, giving a very flat appearance.

8.3 *Court of Chancery*

The Court of Chancery was a prestigious commission, and one that Soane hoped might lead to the rebuilding of the Houses of Parliament. Soane prepared by researching other law courts, sending his apprentices to survey both Middlesex County Sessions House and the Court of the King's Bench at Guildhall; he also reviewed Gandy's drawings of Lancaster Shire Hall [66]. The Court of Chancery was one of seven courts designed to fit into a severely restricted site, with Westminster Hall a substantial obstruction at 28m high, 73m long and 21m deep. Soane originally sited the Court of Chancery in the location of the Court of the King's Bench, to the north of the site. This location was equally obstructed to all sides except the north and there were complaints about the lack of light in the Court of the King's Bench, as well as the Court of Chancery [44].

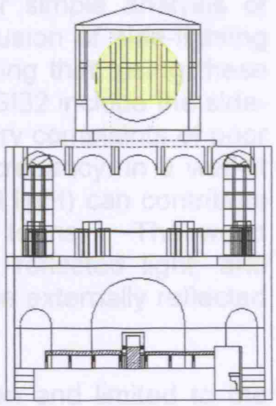
The internal orientation of the court was initially east-west, with the tribunal facing east. Soane reoriented the layout so that the tribunal faced north and created a light court between the Court of Chancery and the rear of the Stone Building. With such an obstructed site, the potential of borrowed light must have outweighed the benefits of an east-west orientation in Soane's mind. The disadvantage of the north facing tribunal is that little direct light would be available, particularly with an ornate tribunal canopy hanging over the dais. The lantern screen was mounted on a soffit, extending by 0.58m into the lantern void. When the lantern screen was removed the soffit remained, and this would have limited the improvement of daylight penetration.

Using the eighteenth century rule of thumb to calculate window area, Soane again exceeded the estimated size of the lantern. Taking into account the loss of window area due to fenestration, the estimate becomes much closer to the actual window area.

		Window Area (m^2)		
	Room volume (m^3)	**Estimated (using rule of thumb)**	**Actual (incl. fenestration)**	**Actual (excl. fenstration)**
Court of Chancery	868.10	29.46	45.60	31.54

The window area with the lantern screen in place is effectively the area of window that can be seen, as indicated by the yellow shading. The proportion of glazing to the total room surface area with the lantern screen is 4.5%, which just classifies as the medium glazing area range of 4 – 10%.

With the lantern screen removed, the glazing area increases to 9.13% of the room area, falling comfortably into the medium glazing area range.



	Room area (m^2)	Window area (m^2) Vertical Lantern	Glazing Area (%) Vertical Lantern
With lantern screen	499.63	22.48	**4.50**
Lantern screen removed	499.63	45.60	**9.13**

The type of glass Soane used in the Court of Chancery is unknown, so it was assumed that clear glass was used.

The horizontal daylight factors calculated with the lantern screen in place did not exceed 1.1%, a level falling below current standards for adequately daylit spaces[9]. The probability of useful daylight illuminance analysis takes into account the daily and seasonal variation of daylight, not evident from the daylight factor alone. This analysis shows that the average horizontal daylight factor of 0.9% only provides sufficient internal daylight between the months of April and August (at least 90% probability, for the majority of the working day). The remaining seven months of the year experience decreasing levels of probability of useful daylight illuminances, with the Court of Chancery in very dim conditions in November and December. The city location of the Court of Chancery, towards the end of the first quarter of the nineteenth century, would have seen more overcast skies than today due to the smoggy conditions caused by the coal-powered economy.

The vertical daylight factors are even lower at a maximum of 0.8% over the dais and 0.3% over the front bench. The Chancellor would have struggled to see the lawyers' faces, peering out into the darkness of the court. Far from providing a "serious character" to the court, the lantern screen introduced a Stygian gloom; an effect which cannot have been lost on Soane.

While the lantern screen's removal improved the horizontal daylight factors, the average value of 1.3% still falls short of today's daylighting standards. The daily and seasonal plot of useful daylight illuminance probabilities shows that the average daylight factor of 1.3% gives a probability greater than 90% for the majority of the working day between April and September, an improvement of one month. The winter months remain poorly illuminated, with the likelihood of very dark afternoons. The small improvement of 0.2% in the vertical daylight factor over the dais would have helped visibility of the Chancellor, but no change was observed in the vertical daylight factors over the front bench. This is because the position of the front bench is such that no daylight penetrates to the measured vertical plane, due to its position on the ground floor facing towards the south wall, only 3.22m away.

Soane's estimate, using the window area rule-of-thumb, and our simple analysis of glazing area, do not take into account the side-lighting. The inclusion of side-lighting would further increase window area and glazing proportion, indicating that, using these guidelines, the space should be well-lit. The daylight factors from AGI32 include the side-lighting, and yet the values are very low, backing up the contemporary complaints of poor light. Analysis of the indirect daylight component explains the discrepancy: in a well-lit space, indirect light (comprising of internally and externally reflected light) can contribute a significant proportion of the overall daylight factor in absolute terms. The wood panelling reduces the wall reflectance, and hence the internally reflected light; and Westminster Hall and the surrounding law courts complex reduce the externally reflected light.

Sunlight penetration is minimal, with and without the lantern screen and limited to the upper gallery level. The ground level does not appear to receive any direct sunlight at all. Several viewpoints were tested in order to verify this.

[9] BS 8206-2:1992 no less than 5% average daylight factor for interiors without supplementary artificial light, and no less than 2% average daylight factor for interiors with supplementary artificial light

The daylight performance results show that complaints of insufficient light were justified. One must have some sympathy with Soane, dealing with a restricted site dominated by Westminster Hall. Were the resultant poorly lit courts an inevitable outcome? Perhaps not, the removal of the residual soffit from the ill-advised lantern screen might have made a small difference. Here also was an opportunity for Soane to use a lantern with sloped glazing, rather than the opaque top, which would have increased daylight penetration. It would seem that Soane was rather more concerned with the appearance of light in the Court of Chancery than the quantity.

9 Conclusions and Future Research

This section outlines the main conclusions of this review, and identifies an opportunity for further research.

9.1 Conclusions

The objective of this review was to form a balanced judgement of Soane's handling of daylight. Soane's reputation as a daylighting innovator, and master of light, was examined in the context of contemporary daylighting, and evaluated through the use of two case studies. Dulwich Picture Gallery and the Court of Chancery were investigated to:

- understand Soane's working practices with regard to daylight design
- determine daylighting performance using daylight factors, useful daylight illuminance and prediction of sunlight penetration

The architectural survey catalogued here shows that that Soane was far from being the first consistent user of top-lighting. Many of his contemporaries used top-lighting, in private houses and public buildings. The prevailing architectural style of the period was neo-classical, and Soane was not alone in being influenced by the classical monuments of Italy through books, drawings and tours. Many of the Palladian principles of proportion were documented in architectural publications and building manuals of the eighteenth century, including advice on sizing of windows for adequate provision of light. Top-lit buildings designed by other architects of the period demonstrate the use of this solution as an aesthetic as well as functional response to the site, for example George Dance's Guildhall and Taylor's Transfer Office.

The study of Soane's design process through the evolution of his ideas for Dulwich Picture Gallery and the Court of Chancery shows an iterative approach, familiar to architects and designers today. Soane was not a "natural" daylighting designer. His indecision at Dulwich, vacillating between roof lanterns and clerestory windows, betrays a hesitant manner. His final design used traditional lanterns with vertical glazing, and continued the precedent for top-lighting of galleries set by the Uffizi Gallery in Florence, the Royal Academy's Great Room on Pall Mall and Christie's Auction Room, also on Pall Mall. Soane's response to the limited budget at Dulwich led to the use of small glass panes in order to keep to his estimate, and hence the reduced window area due to the larger proportion of fenestration to glass. The octagonal shape of the lanterns was an effective compromise between cost and performance.

Soane followed convention in his choice of top-lighting for the Court of Chancery. Soane researched other courtrooms before starting his design, reviewing plans for Middlesex Sessions House drawn by his apprentices and Lancaster Shire Hall, drawn by Gandy. Sawyer describes Soane's approach to the interior design of the Court of Chancery as uncoordinated: Soane battled with the limitations of the restricted site, the many requirements of the lawyers and management by committee. His attempts to design a space fitting to the authority and drama of the court led to an interior full of complex elements, the most unusual of which was the lantern screen. This attempt at filtering the light to provide a lumiere mysterieux was not successful, and the screen was soon removed – a case of on-site trial and error. No architectural models exist, other than Soane's own house (now the Soane Museum), to suggest that Soane experimented with the daylighting design of either Dulwich or the Court of Chancery. Both Dulwich Picture Gallery and the Court of Chancery appear to be top-lit in response to function and common practice for buildings of their type. Soane may have been innovative in his use of new building materials and technologies [67], but these case studies show that, from a functional perspective, he trod a traditional path in daylighting.

Daylighting performance of Dulwich Picture Gallery and the Court of Chancery has been considered here in terms of adequate light in worst-case conditions. On this basis, the average daylight factors in the interiors, as built, of 2.0% and 1.3% respectively fall short of current daylight standards.

This review has not found evidence to sustain Soane's daylighting "superstar status" [68]. He neither invented, nor began to use, new methods that others had not applied before him. Soane simply built on the established principles of the time. Where he is different to his contemporaries is in his attachment to themes that he adopted [69]. Given that so little of his work remains, perhaps our current admiration is influenced by his museum with its extensive collections, and picturesque top-lighting effects.

9.2 Future Research

It would be interesting to perform the same daylighting analysis on a top-lit building designed by one of Soane's contemporaries, for comparison with the results presented here. The choice of architect and building clearly rests on the available drawings, as fellow architects were not so prescient as Soane in ensuring the preservation of their drawings and papers. A suitable candidate would be the Royal College of Surgeons at Lincolns Inn Fields, designed by George Dance the Younger with James Lewis. Sufficient drawings exist from which to construct a computer model [70], and the results would be of greater significance given that Dance was Soane's closest and most influential colleague.

10 References

1. Parry C.M. "Lighting in the architecture of Sir John Soane", Lighting Research & Technology Vol. 29 Issue 3 1997, p.102
2. Stroud D. "The architecture of Sir John Soane", Studio 1961, p.25
3. Dean P. "Sir John Soane and London", Lund Humphries 2006, p.39
4. Phillips D. "Daylighting: Natural Light in Architecture", Architectural Press 2004, p.3
5. Lam W.M. "Sunlighting as Formgiver for architecture", Van Nostrand Reinold 1986, p.139
6. Millikin S. "The Tribune in English Architecture", The Burlington Magazine Vol. 112 Issue 808, July 1970, p.442
7. Phillips D. "Daylighting: Natural Light in Architecture", Architectural Press 2004, p.45
8. Lam W.M. "Sunlighting as Formgiver for architecture", Van Nostrand Reinold 1986, p.138-139
9. Watkin D. "Sir John Soane Enlightenment Thought and the Royal Academy Lectures", Cambridge University Press 1996, p.589
10. Watkin D. "Sir John Soane Enlightenment Thought and the Royal Academy Lectures", Cambridge University Press 1996, p.36
11. Watkin D. "Sir John Soane Enlightenment Thought and the Royal Academy Lectures", Cambridge University Press 1996, p.214
12. Baker N., Fanchiotti A., Steemers K. ed. "Daylighting in Architecture: a European Reference Book", James & James 1993, p.1.13
13. Craddock N. "Sir John Soane and the Luminous Environment", University of Cambridge 1995, p.33
14. Mellinghoff G.-T. "Soane's Dulwich Picture Gallery Revisited" in "John Soane", Academy Editions 1983, p.91
15. Stroud D. "George Dance, Architect, 1741-1825", Faber and Faber 1971, p.184
16. Summerson J. "Soane: The Case-History of a Personal Style", RIBA Journal, January 1951, p.83-91
17. Summerson J. "Soane: the Man and the Style" in "John Soane", Academy Editions 1983, p.11
18. Stroud D. "Henry Holland His Life and Architecture", Country Life 1966, p.37
19. Stillman D. "English Neo-classical Architecture", Zwemmer 1988, Volume Two, p.358
20. Summerson J. "Soane: The Case-History of a Personal Style", RIBA Journal, January 1951, p.85
21. Richardson M. & Stevens S. ed. "John Soane: Architect. Master of Space and Light", Royal Academy of Arts 1999, p.196
22. Craddock N. "Sir John Soane and the Luminous Environment", University of Cambridge 1995
23. Ayres J. "Building the Georgian City", Yale University Press 1998, p. 23-27
24. Fontoynont M. ed. "A study of daylighting devices at the beginning of the 19th century" in "Daylight Performance of Buildings", James & James, p.103-106
25. Parry C.M. "Lighting in the architecture of Sir John Soane", Lighting Research & Technology Vol. 29 Issue 3 1997, p.95-104
26. Cruickshank D. "Illuminating Scholarship", The Architects Journal Vol. 210 Issue 11 1999, 23 September, p.50
27. Sharp D. "The Illustrated Encyclopaedia of Architects and Architecture. New York: Quatro Publishing 1991, p.144
28. Mellinghoff G.-T. "Soane's Dulwich Picture Gallery Revisited" in "John Soane", Academy Editions 1983, p.82
29. Waterfield G. "Picture Galleries of Regency England", York Georgian Society Annual Report 1998, p.13
30. Millikin S. "The Tribune in English Architecture", The Burlington Magazine Vol. 112 Issue 808, July 1970, p.445

31. Stroud D. "George Dance, Architect, 1741-1825", Faber and Faber 1971, p.162
32. Teyssot G, Levine J. "The Simple Day and the Light of the Sun: Lights and Shadows in the Museum", Assemblage No. 12, April 1990, p.76
33. Atkin D. "Thomas Hope's House in Duchess Street", Apollo March 2004
34. Waterfield G. "Soane and After: The Architecture of Dulwich Picture Gallery", Dulwich Picture Gallery 1987, p.10
35. Chun D. "Sir John Leicester's Gallery of British Art: Public display, private glory", Journal of the History of Collections, Vol. 13 No. 2 (2201), p.179
36. Watkin D. "Soane and his contemporaries" in "John Soane", Academy Editions 1983, p.52
37. Dean P. "Sir John Soane and London", Lund Humphries 2006
38. Cannon-Brookes S. "Daylight in museum galleries: quantitative evaluation using scale models", PhD Thesis, Cardiff 1995, p.19
39. Nevola F. "Soane's Favourite Subject: The Story of the Dulwich Picture Gallery", Dulwich Picture Gallery 2000
40. Waterfield G. "Soane and After: The Architecture of Dulwich Picture Gallery", Dulwich Picture Gallery 1987, p.33
41. Waterfield G. "Soane and After: The Architecture of Dulwich Picture Gallery", Dulwich Picture Gallery 1987, p.47
42. Horden R. Associates. "The Dulwich Picture Gallery Study Project Report", 1994, p5.5
43. Sawyer S. E. "Soane at Westminster: Civic Architecture and National Identity, 1789-1834", DPhil Thesis, Columbia University 1999, p.539
44. Sawyer S. E. "Soane at Westminster: Civic Architecture and National Identity, 1789-1834", DPhil Thesis, Columbia University 1999, p.552
45. Wedgwood A. "Soane's Law Courts at Westminster", AA Files 24, p.40
46. Sawyer S. E. "Soane at Westminster: Civic Architecture and National Identity, 1789-1834", DPhil Thesis, Columbia University 1999, p.554
47. CIBSE "Lighting Guide LG10: Daylighting and window design", 1999
48. http://idmp.entpe.fr/ accessed 3 September 2006
49. Nabil A. & Mardaljevic J. "Useful daylight illuminance: a new paradigm for assessing daylight in buildings", Lighting Research & Technology, Vol. 37 No. 1 (2005), p.41-59
50. Hopkinson R.G. et al "Daylighting", William Heinemann 1966, p.18
51. Stroud D. "The architecture of Sir John Soane", Studio 1961, p.134
52. Bergman L., Rogowitz B. & Treinish L. "A Rule-based Tool for Assisting Colormap Selection", Proceedings of the IEEE Computer Society Visualization 1995, October 1995, p.118-125
53. CIBSE "Lighting Guide LG8: Lighting for museums and art galleries", CIBSE 1994, p.23
54. Cruickshank D. & Burton N. "Life in the Georgian City", Viking 1990, p.148
55. Ayres J. "Building the Georgian City", Yale University Press 1998, p. 193
56. Cruickshank D. & Harrap J. "Using technology to save Soane", The Architects' Journal, 3 March 1993, p.40-41
57. Ayres J. "Building the Georgian City", Yale University Press 1998, p. 190
58. Pinkhorn M. "The Window Tax, 1696-1851", Blackmansbury Journal, Vol. 3 & 4 August/October 1966, p.19-27
59. Ayres J. "Building the Georgian City", Yale University Press 1998, p. 189
60. Waterfield G. "Soane and After: The Architecture of Dulwich Picture Gallery", Dulwich Picture Gallery 1987, p.7
61. Waterfield G. "Soane and After: The Architecture of Dulwich Picture Gallery", Dulwich Picture Gallery 1987, p.35
62. Mellinghoff G.-T. "Soane's Dulwich Picture Gallery Revisited" in "John Soane", Academy Editions 1983, p.91
63. Watkin D. "Sir John Soane Enlightenment Thought and the Royal Academy Lectures", Cambridge University Press 1996, p.598

64. Baker N., Fanchiotti A., Steemers K. ed. "Daylighting in Architecture: a European Reference Book", James & James 1993, p.5.7
65. Davey P. "Spirit of Soane", Architectural Review, Vol. CCVIII No. 8, August 2000, p.72-76
66. Sawyer S. E. "Soane at Westminster: Civic Architecture and National Identity, 1789-1834", DPhil Thesis, Columbia University 1999, p.500
67. Wilmert T. "Heating Methods and Their Impacts on Soane's work: Lincoln's Inn Fields and Dulwich Picture Gallery", The Journal of the Society of Architectural Historians, Vol. 52 No. 1 (March 1993), p.26-58
68. Stamp G. "Slightly Subhuman?", Apollo, August 2006
69. Summerson J. "Soane: The Case-History of a Personal Style", RIBA Journal, January 1951, p.87
70. Lever J. "Catalogue of the Drawings of George Dance the Younger (1741-1825) and of George Dance the Elder (1695-1768)", Oxford University Press, March 2004, p.159-193

11 Bibliography

Ballantyne A. "First principles and ancient errors: Soane at Dulwich", Architectural History Vol. 37, 1994, p.96-111

Bolton A.T. "The Works of Sir John Soane", London 1924

BSI "BS8206-2:1992 Lighting for buildings - Part 2: Code of practice for daylighting", BSI 1992

CIBSE " Lighting Guide LG10: Daylighting and window design", CIBSE 1999

Connelly J. L. "The Grand Gallery of the Louvre and the Museum Project: Architectural Problems", The Journal of the Society of Architectural Historians, Vol.31, No. 2, May 1972, p.120-132

Cruickshank D. & Wyld P. "London: the Art of Georgian Building", Architectural Press 1975

Darley G. "John Soane: an accidental romantic", Yale University Press 1999

Davies C. "Dulwich Picture Gallery, the first independent purpose-built picture gallery" Architects Journal 24 April 1985, p.45-65

Ghafouri M. & White R. "A History of Museum Daylighting" in "International Daylighting Conference Proceedings 1986", p.483-487

Harrap J. & Cruickshank D. "Using technology to save Soane", Architects Journal 3 March 1993, p.35-44

Harris J. "Soane's Classical Triumph: a lost Westminster masterpiece revealed", Apollo, Vol. 135 No.363, May 1992, p.288-290

Lank H. "The Function of Natural Light in Picture Galleries", The Burlington Magazine, Vol. 126 No. 970, January 1984, p.4-7

Morris R. "Lecture on Architecture", London 1759

Pain W. "The Carpenter's and Joiner's Repository", London 1787

Richardson M. "John Soane: The Business of Architecture", Georgian Group Symposium 1991, p65-72

Richardson M. Soane's Use of Drawings", Apollo, Vol. 131 No. 38, p. 234-240

Sidlauskas S. "Creating Immortality: Turner, Soane, and the Great Chain of Being", Art Journal, Vol. 52 No. 2, Summer 1993, p.59-65

Stillman D. "The Gallery for Lansdowne House: International Neoclassical Architecture and Decoration in Microcosm", The Art Bulletin, Vol. 52 No. 1, March 1970, p.75-80

Summerson J. "Georgian London", Barrie & Jenkins 1988

Teyssot G. & Levine J. ""The Simple Day and the Light of the Sun": Lights and Shadows in the Museum" Assemblage, No. 12, August 1990, p.58-63

Thornton P. "Lit Up With Gorgeous Hues: More Light on Soane?", Country Life, 19 December 1985, p.978-980

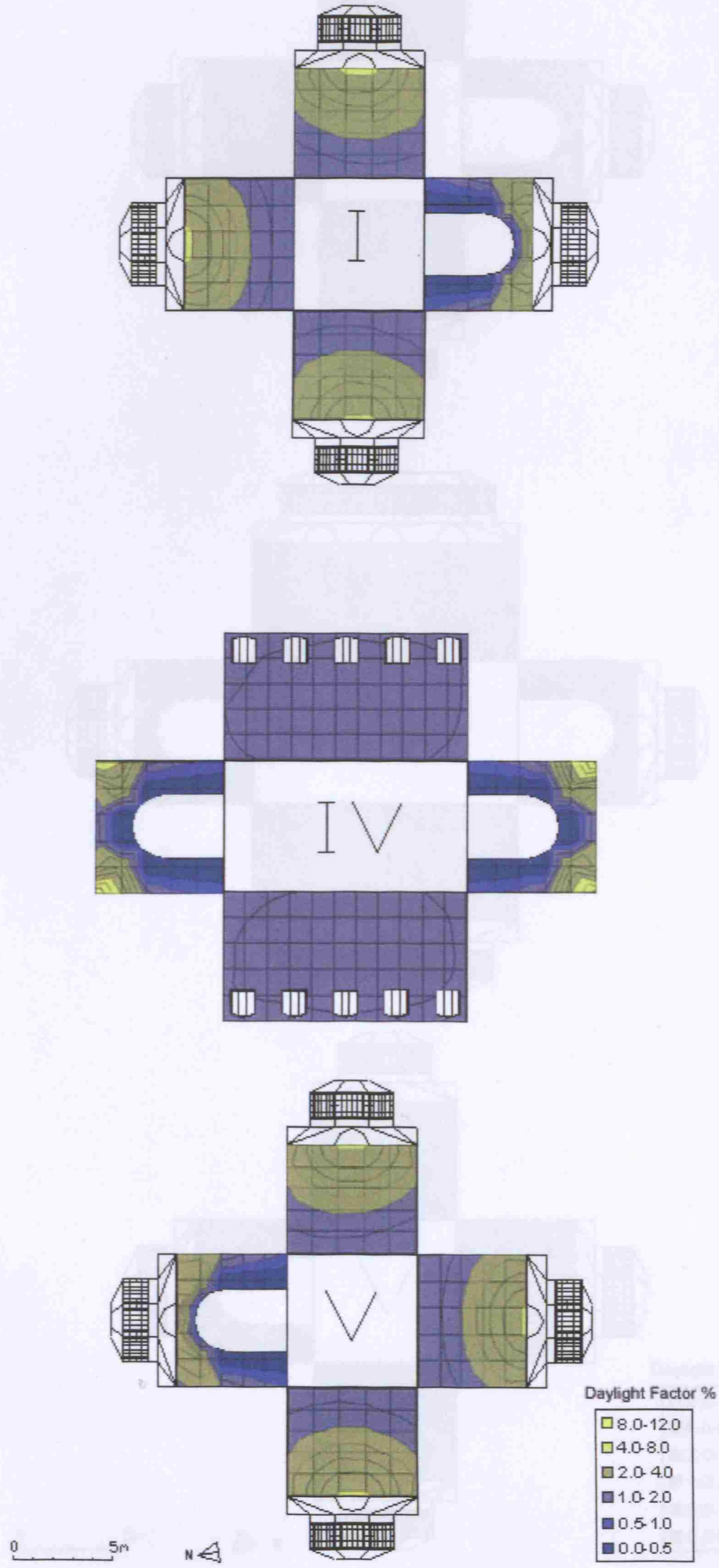
Wilton-Ely J. "The Architectural Models of Sir John Soane: A Catalogue", Architecturtal History, Vol. 12, 1969, p.5-38

http://www.british-history.ac.uk/place.asp?gid=74&region=1 accessed 9 September 2006

http://www.research.ibm.com/people/l/lloydt/color/color.HTM accessed 9 September 2006

Appendix I Dulwich Picture Gallery Vertical Daylight Factors, Galleries I, IV, V

I.1 Dulwich Picture Gallery Test 1 Vertical Daylight Factors



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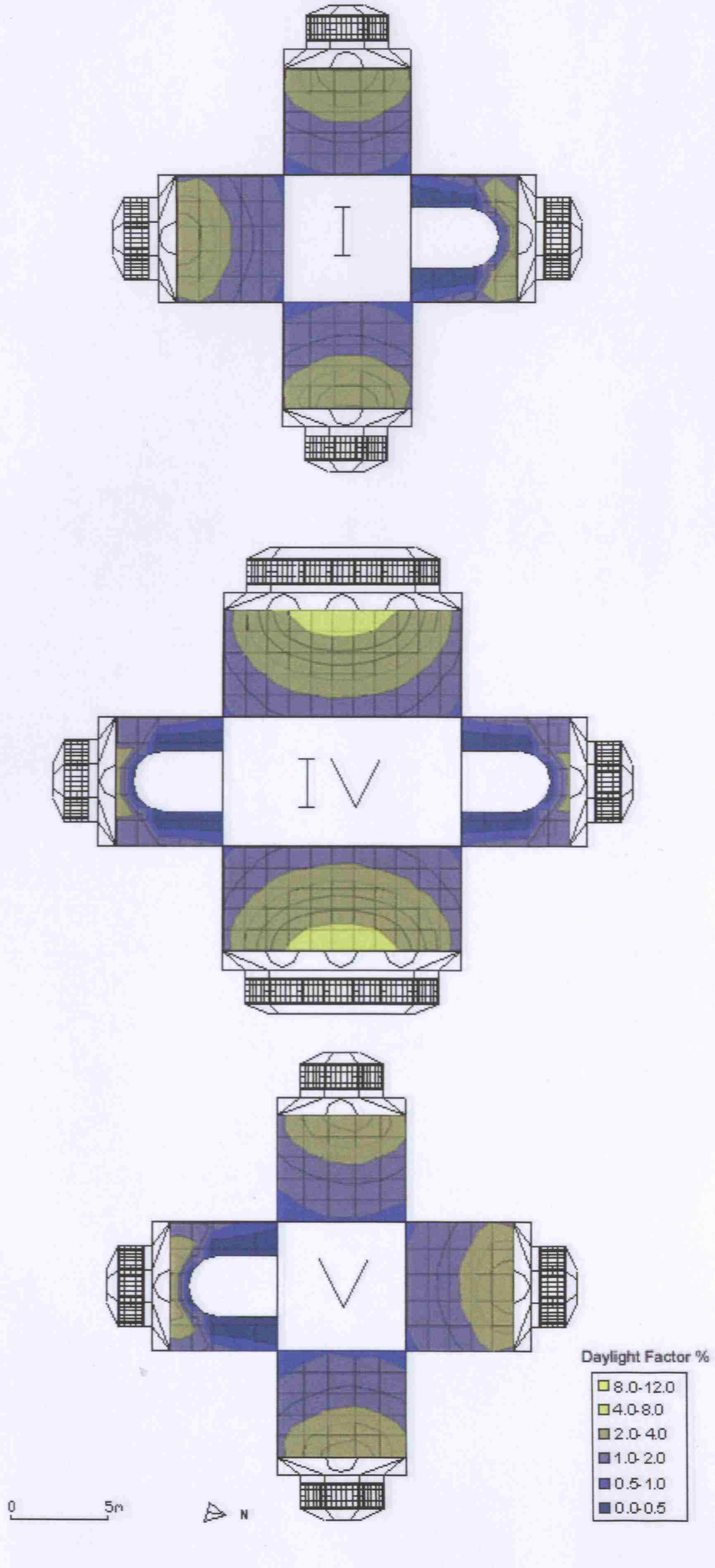

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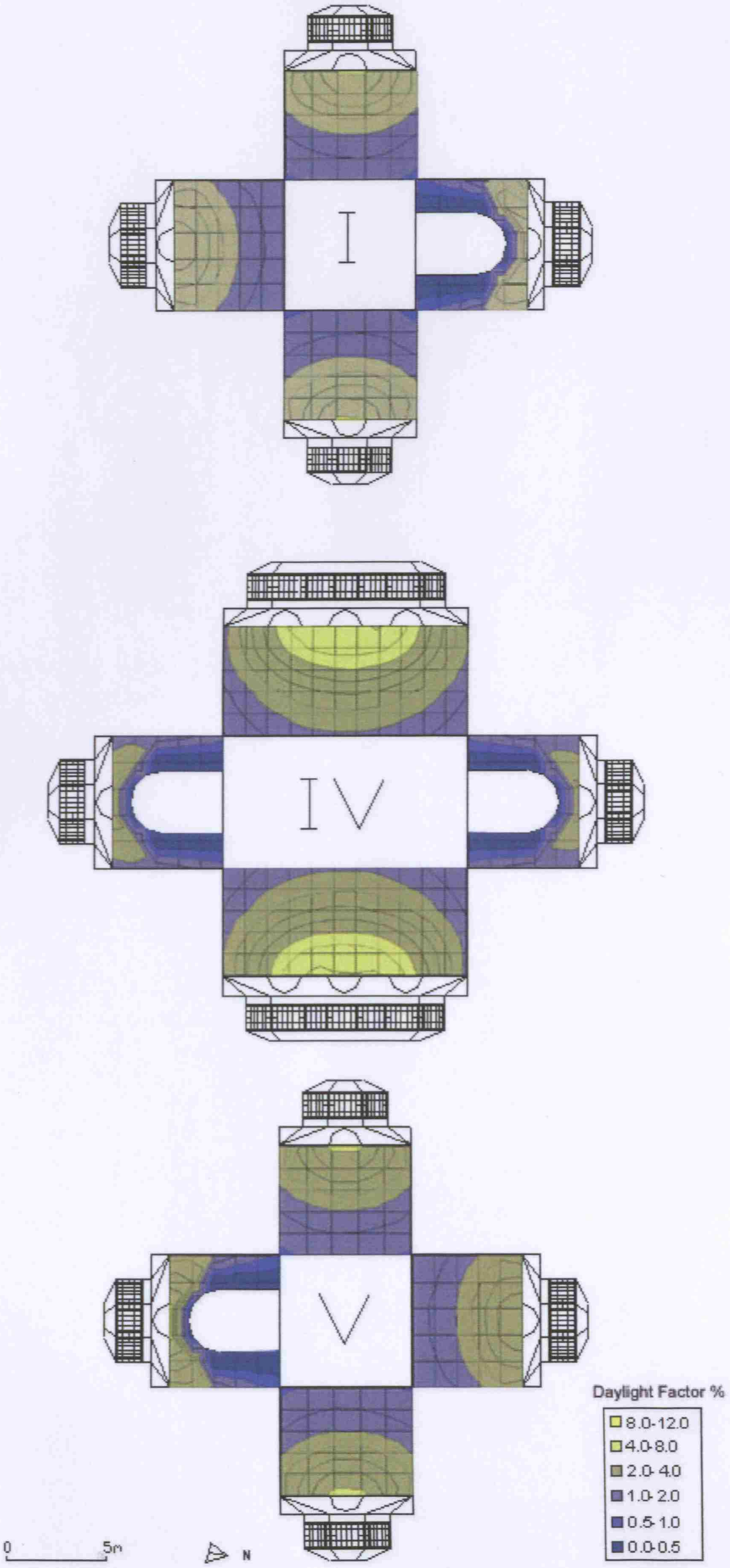

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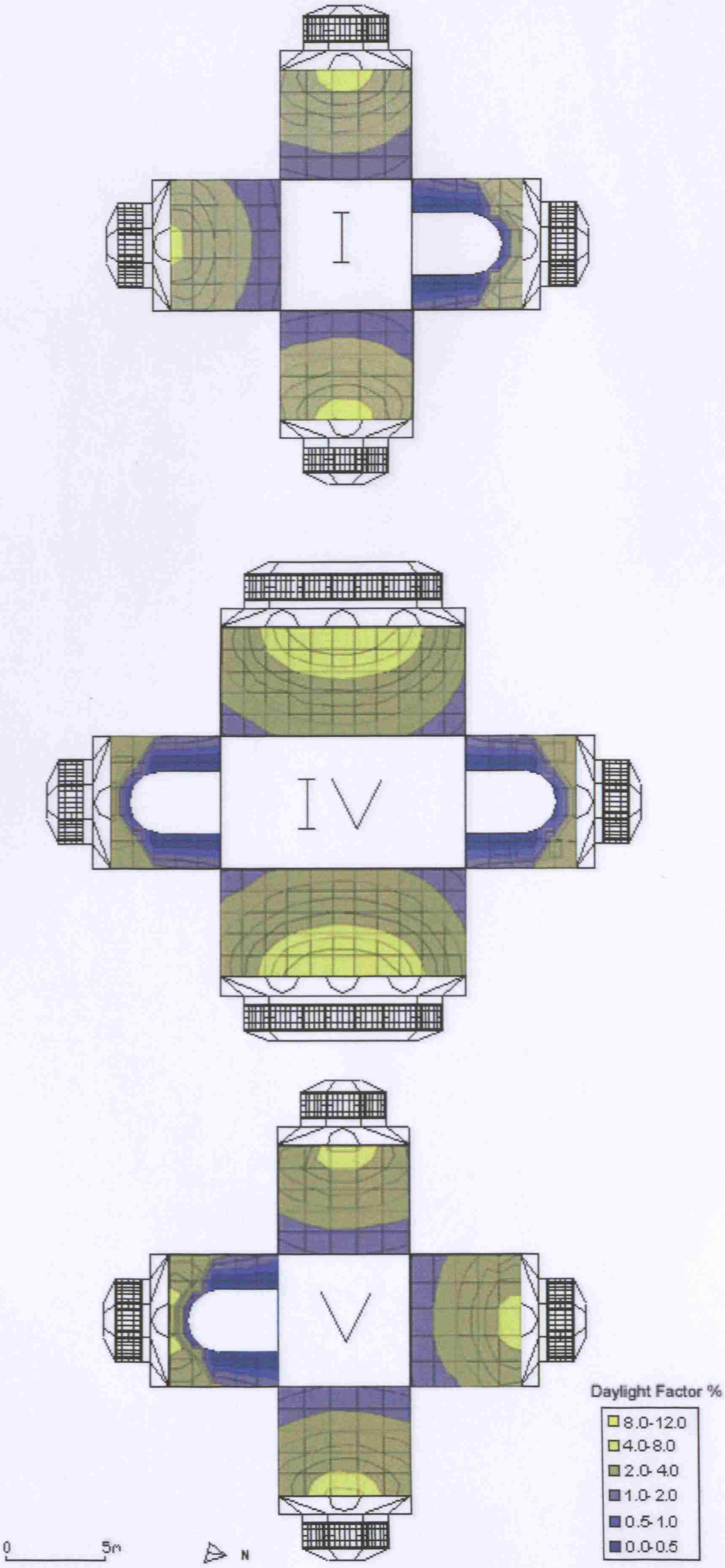
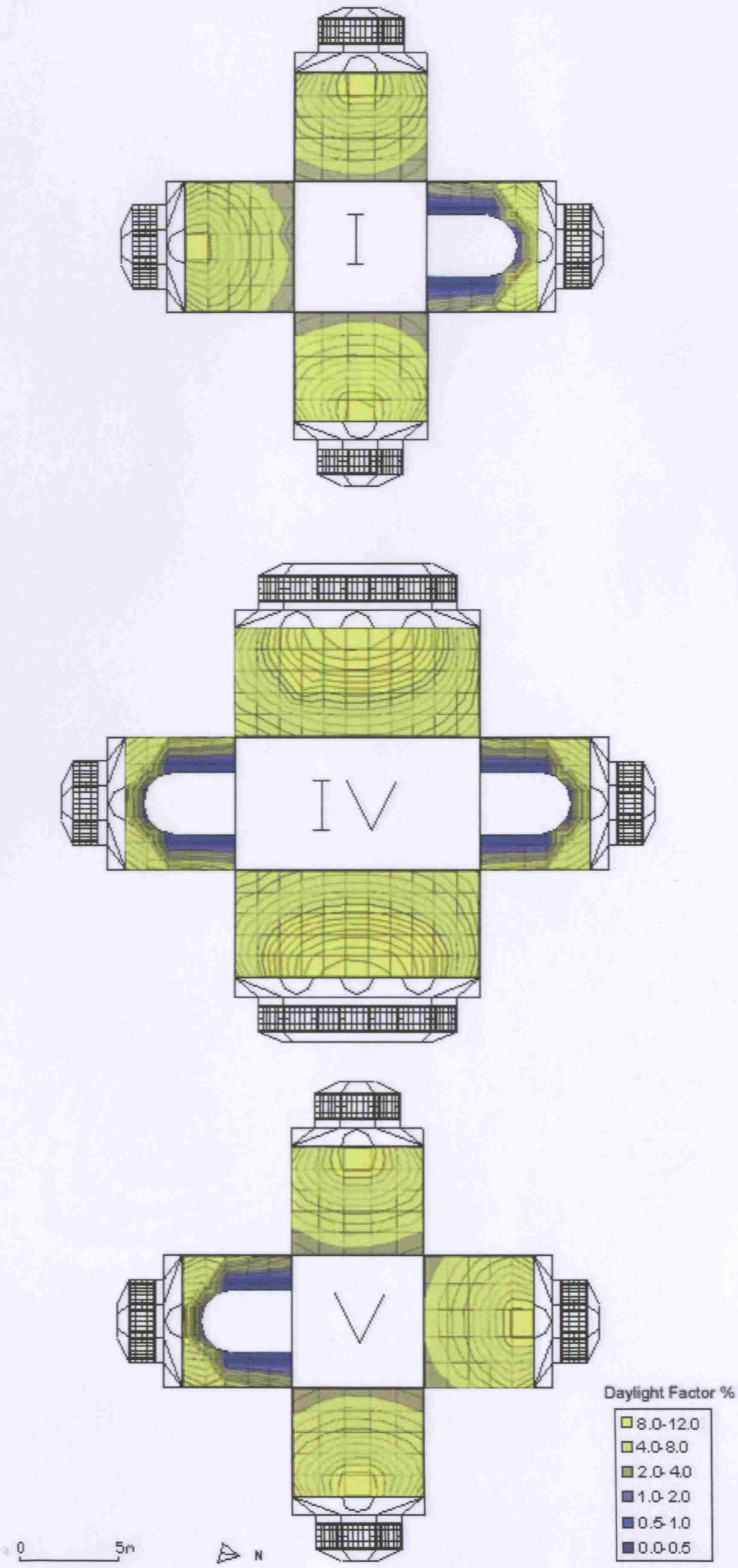
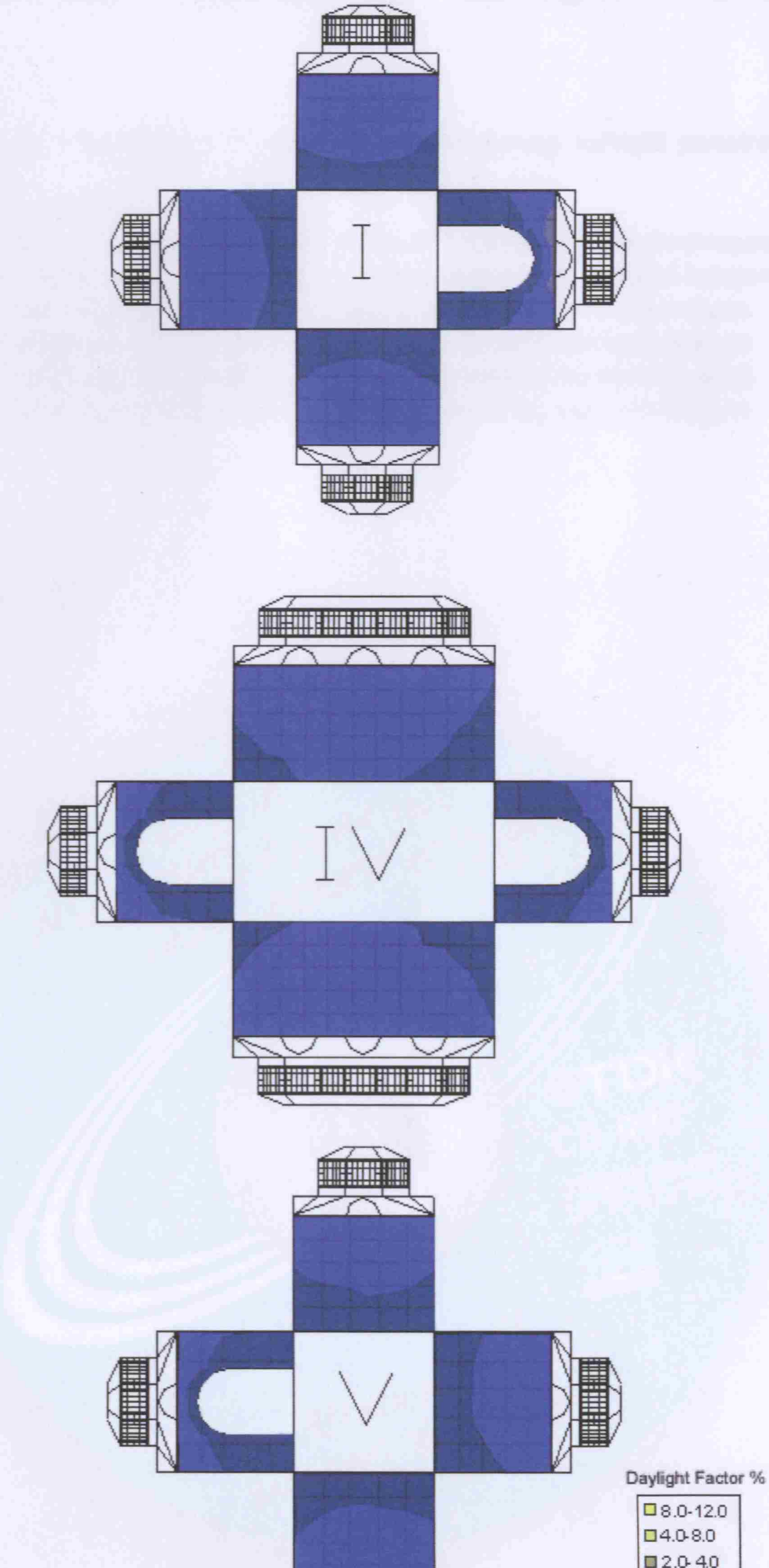


I.5 Dulwich Picture Gallery Test 5 Vertical Daylight Factors



I.6 Dulwich Picture Gallery Test 6 Vertical Daylight Factors



Appendix II CD Containing Sunlight Penetration Images

CD Contents:

- README.txt – file listing CD contents and explaining sunlight penetration image numbering
- copy of this report
- Chancery Test 1 Sunlight Penetration folder, containing sunlight images
- Chancery Test 2 Sunlight Penetration folder, containing sunlight images
- Dulwich Test 1 Sunlight Penetration folder, containing sunlight images
- Dulwich Test 2 Sunlight Penetration folder, containing sunlight images
- Dulwich Test 3 Sunlight Penetration folder, containing sunlight images
- Dulwich Test 5 Sunlight Penetration folder, containing sunlight images